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UNIVERSITY OF ALBERTA

AN ANALYSIS OF THE WEAR OF POLYMERS

BY

NARENDRA S. VISWANATH ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of **DOCTOR OF PHILOSOPHY**.

DEPARTMENT OF MECHANICAL ENGINEERING

Edmonton, Alberta
FALL 1992

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ABSTRACT

Potential for wear exists whenever there is relative motion between two solid bodies under load. Polymers possess unique properties suitable for many tribological applications. The main aim of the research was to investigate and analyze the friction and wear of polymers under different operating conditions and polymer material properties. A series of laboratory experiments were performed on thirteen different commercially available polymers as pins and HTSR 4140 steel and AISI 1018 steel as counterface disks on pin-on-disk machines.

Two types of analyses were performed. In the first, a dimensional analysis was carried out to develop an empirical wear equation in which the volume of polymer material worn during sliding on a horizontal pin-on-disk machine was expressed in terms of the operating variables and material properties of the polymer. The dimensionless wear coefficient was determined for each polymer using both a linear and an exponential relationship of volume loss with other variables. It was found that a better correlation could be obtained using an exponential relationship. In the second analysis, the influence of the operating variables on the wear and coefficient of friction was studied using both a horizontal pin-on-disk and a vertical pin-on-disk machine. The influence of operating variables, counterface material and its roughness on the friction and wear behaviour of polymers was observed. The counterface became "modified" with wear debris for some of the polymers tested. The vertical pin-on-disk configuration also enabled wear tests at different radii on the counterface to be investigated while maintaining a constant surface speed. Results from both pin-on-disk machines showed the influence of the type of configuration on the friction and the wear of polymers tested.

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LIST OF SYMBOLS

E: Modulus of Elasticity
H: Indentation Hardness
K: Thermal Conductivity
L: Sliding Length
P: Contact Pressure
T: Duration of Test or Sliding Time
V: Volume of Worn Material
W: Contact Force or Normal Load at the Junction
$\{p,q,r,s\}$: Exponential Parameters
v: Sliding Speed
C_p: Specific Heat
k_w: Wear Constant or Coefficient
α: Counterface Roughness
γ: Surface Free Energy
μ: Coefficient of Friction

LIST OF ABBREVIATIONS

AISI:	American Iron and Steel Institute
FRP:	Fibre Reinforced Plastics
HDPE:	High Density Polyethylene
HTSR:	Heat Treated and Stress Relieved
LDPE:	Low Density Polyethylene
POM:	Polyoxy Methylene (Delrin)
PP:	Polypropylene
PTFE:	Poly Tetra Fluoroethylene
PVC:	Poly Vinyl Chloride
SEM:	Scanning Electron Microscope
TFE:	Tetra Fluoroethylene
UHMWPE:	Ultra High Molecular Weight Polyethylene
c.l.a. (Ra):	centre line average
c.o.f.:	coefficient of friction
rpm:	revolutions per minute
Teflon(m):	Teflon(mechanical)
Teflon(v):	Teflon(virgin)

1. INTRODUCTION

Wear is the loss of material from one surface caused by the interaction with another surface. The scientific research committee of the Organization for Economic Co-operation and Development has defined wear as "the progressive loss of substance from the operating surface of a body occurring as a result of relative motion of the surface" [1]. All tribological processes, i.e., friction and wear of interacting materials, begin with two basic phenomena; (i) the formation of the contact area under an applied load, and (ii) the initiation of relative motion between the contacting bodies by overcoming static friction.

In most situations wear is associated with the formation and growth of junctions because of asperity contact. Surfaces in sliding applications are not perfectly smooth and possess varying degrees of roughness so that contact between two solids occurs only at a finite number of isolated points resulting in an area of contact which is a fraction of the apparent area. At these regions of asperity contact, very high localized stresses occur. As motion is initiated, high strain rates develop causing junctions to be broken leading to new asperity contacts. As loads are increased, a larger number of asperities are developed and crowded junctions are formed. Subsequent deformations occur in the cohesively weaker of the two materials in contact causing wear fragments or debris to be formed. Wear occurs at the surface or below the surface. For static contact it usually results in subsurface cracks. For dynamic contact wear occurs either at the surface or near the surface due to shearing of the asperities.

Wear is classified in the following specific terms [2]; (i) wear mechanism, (ii) wear process, and (iii) wear mode. The wear mechanism involves basic atomic and molecular interactions, such as atomic diffusion, monolayer film formation, adhesion, dislocation interactions and surface chemical reactions. The wear mode or wear type is a unique combination of basic wear processes where different wear processes dominate and operate to produce observed wear modes. The relative importance of various processes in making up the wear mode need not be constant but may change over time.

The eight most commonly observed modes of wear are;

Adhesive wear, Abrasive wear, Fatigue wear, Delamination wear, Impact wear, Fretting wear, Cavitation and Erosion wear, and Chemical and Oxidative wear.

Understanding the wear of polymers against metal surfaces is important from a practical standpoint since polymers are being used more and more in sliding applications. Normally, wear in polymer materials occurs as a result of strong adhesive interaction, fatigue, macro-shearing, abrasive, thermal and oxidation interaction, corrosion cavitation, etc. Many wear processes take place simultaneously, complicating the analysis. Transfer of polymer wear debris as film on to the counterface during sliding is a major factor in the study of the wear of polymers. This does not occur to the same extent in the wear of metals. The influence of this polymer film smooths out the counterface reducing both friction and wear rate creating a polymer sliding on a polymer [3].

It is necessary to investigate the result of any wearing process in the destruction of critical surfaces. Further results of this destruction are debris generation and a change in the wear mechanism/process. Despite the relatively low strength of plastics, they possess many excellent sliding characteristics; relatively low surface reactivity, high molecular weight yielding a high specific strength and stiffness, an absence of gross seizure, a natural damping capacity to absorb vibrations and noise, and a capacity to slide smoothly and easily with little or no lubrication and maintenance [4]. The significant features of polymer/metal friction and wear interaction are due to the low surface energy, high oxidation resistance, low hardness, low heat conductivity and strong temperature dependence of mechanical properties of all polymers [5]. Polymers and their composites have been widely used in many sliding applications because of the unique inherent tribological properties such as low friction and high wear resistance. The various applications of polymers are, aerospace, automotive, bio-medical, extruded and cast components, coatings to metallic products, etc., where the technical features of polymers allows the designers to adopt considerably more complex designs by using the properties effectively.

There are no universal theories governing the wear of polymers. The variety of conditions, which are usually in a combination of one or more elementary forms that are responsible for wear, makes its study a complex subject. Wear is not an intrinsic property of the material. The control and prevention of wear can be achieved with a better understanding of the different wear mechanisms and the factors which influence them through laboratory models. A reliable relationship between the wear of polymers and the operating variables and polymer material properties is desirable in order to obtain a better understanding of the wear behaviour of polymers under a variety of conditions and applications.

In the research described in this thesis, experiments were conducted on two pin-on-disk machines with thirteen commercially available polymers as pins and two metal counterface disks; heat treated and stress relieved (HTSR) 4140 steel, and cold rolled AISI 1018 steel. The experiments were performed in an unlubricated condition during sliding of polymer pins on the metal counterface at ambient temperature and humidity with the metal disks cooled to remain close to room temperature. The reasons for choosing ambient air conditions were because of a similarity to industrial applications. The polymers tested were analyzed for their wear behaviours under different operating conditions, such as load, speed, duration of test, and surface roughness of the counterfaces. Scanning electron micrographs were used to assist in the analysis of the wear mechanisms.

Two types of analyses were carried out based on the results obtained: the first analysis involved the development of an equation for the wear of polymers using dimensional analysis. The experimental data from sliding of six polymers on HTSR 4140 steel and AISI 1018 steel counterfaces, on the horizontal pin-on-disk machine was used to develop the equation. This equation related the volume of polymer material worn with different operating conditions and material properties (surface energy, modulus of elasticity, thermal conductivity and specific heat) of a polymer through a dimensionless wear coefficient. The empirical wear equation was derived using both linear and non-linear relationships between the operating variables and the volume loss. A comparison of both types of models has been carried out.

The second analysis involved the wear and friction results from both horizontal and vertical pin-on-disk machines. Comparison of friction and wear behaviour at different speed and loading conditions with both counterfaces has been carried out. The vertical pin-on-disk machine was used to evaluate the effects of disk speed on the wear and friction behaviour of polymers at different counterface roughnesses. The friction and wear analysis was also carried out for different polymers sliding against both counterfaces under different operating conditions. Lastly, the results from two pin-on-disk machines are compared for the effect of test configuration on the friction and wear behaviour. The scanning electron micrographs of the worn surfaces are used to explain the different wear modes observed with polymers, and to show the transfer of polymer wear debris on to the metal counterface.

In the following text, Chapter 2 deals with wear and friction processes in polymers and the factors influencing them; Chapter 3 deals with the history and development of an analytical dimensionless equation for the wear of polymers; Chapter 4 deals with the statistical analysis, sensitivity and uncertainty analysis, and appropriateness of linearity or non-linearity of the wear equation; Chapter 5 discusses the effects of operating variables and the testing configuration on the friction and wear behaviour of different polymers on both horizontal pin-on-disk and vertical pin-on-disk configurations.

2. WEAR MECHANISMS IN POLYMERS

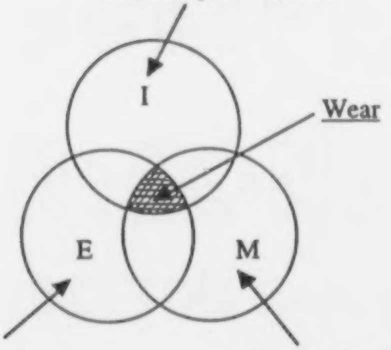
Metal-polymer interaction can be described as a tribo-chemical reaction [6]. A tribo-chemical reaction leading to a wear process is a material interaction due to intermolecular forces either between the interacting bodies or between the interacting solid bodies and the environmental atmosphere. The system comprises polymeric (P) and metallic (M) components that interact in an operative environment (E) under the given conditions of load (L), speed (v) and temperature (T) resulting in products of wearing of metal-polymer tribo-system (PWMPS) as shown in the equation. The schematic of a wear system is shown in Figure 2.1.

$$M + P + E \xrightarrow{L,\ v,\ T} PWMPS$$

$$\text{Wear} = I \cap E \cap M$$

Internal Properties

Surface Energy,
Heat Conductivity,
Modulus of Elasticity,
Morphology,
Fibre Orientation,
Plasticity, Fracture,



External Properties

Load, Sliding Speed,
Time, Surface Roughness,
Temperature,
Chemical Environment,
Materials Combination

Wear Mechanisms

Adhesion,
Abrasion,
Fatigue,
Delamination

Fig. 2.1 : Schematic of a Wear System [118] {Modified from Hornbogen, E.: Werkstoffeigenschaften und Verschleiss, Metall 12 (1980) 1079}

2. 1. TYPES OF POLYMER WEAR

The common types of wear observed in polymers are as follows: Adhesion, Abrasion, Fatigue, Delamination. These are explained in more detail below.

2. 1. 1. ADHESIVE WEAR:

Adhesive wear in polymers arises as a result of a process by which isolated spots on two sliding surfaces adhere together momentarily and eventually shear. High local pressure between contacting asperities is experienced when surfaces slide against each other causing plastic deformation leading to adhesion and to the formation of local junctions. With further motion under load these junctions rupture resulting in the transfer of some material from one surface to the other in the form of wear debris [7-9]. The interfacial adhesive strength and shear strength of the bulk polymer control the transfer of materials [10]. This transfer of polymer is also due to the large strain produced in the asperity tips causing deformation in the cohesively weaker of the two surfaces in contact [7,11].

The effect of the adhesive interactions between two superficial layers of sliding pairs is the phenomenon of material transfer [3,12,13]. Zalisz et al. [14] have concluded that there are three effects that can contribute to material transfer: the deformation of surface asperities under load; the fracture of material in the substrate; and the adherence of this material to the other surface. During the mechanism of sliding friction of polymers, the asperities adhere instantly upon contact so as to form an adhesive joint [15,16]. Transfer from a polymer to a metal counterface occurs because cohesion within the surface layer will be weakened by repeated stress cycles [17,18]. During the sliding of polymers, the surface of each solid is involved in the material transfer in the form of a thin film of polymer build up and the growing in size of this transfer particle to a thin film results in material removal as wear debris [19-23].

2. 1. 2. ABRASIVE WEAR:

Abrasive wear is the displacement of material caused by the presence of hard particles between the two surfaces in relative motion or by the presence of hard protuberances on one or both of the moving surfaces resulting in tearing, micro-cutting, scratching, micro-ploughing (combined with high plastic deformation), and eventually, micro-cracking of the polymer surface [24-26]. Disintegration of the materials caused by simple actions of the indentor causing microscopic cutting leads to abrasive wear. Abrasive wear is controlled by the cohesive strength or toughness of the polymer [27]. Polymers are extremely susceptible to abrasive wear because of their relatively weak cohesive strength [22].

A wide range of studies by Lancaster [28-31] on the wear of polymers sliding against metal surfaces have indicated that if the surface roughness is less than 0.05 microns the wear is largely due to an adhesive mechanism. If the roughness is greater than 0.05 microns, the wear is largely due to abrasion of the polymer. The abrasive wear process involves plastic deformation and shear, and it is found that for abrasion the dominant material property is the energy to fracture of the polymer. On rough surfaces with sharp asperities (high curvature) the wear mechanism has been observed to be predominantly abrasive [32,33] and a layered polymer film is found on the metal surface due to wear debris produced from the drawing of the material from the polymer surface [34,35].

2. 1. 3. FATIGUE WEAR:

Fatigue wear in polymers occurs when the polymer undergoes cyclic deformation causing separation of fragments from the surface by fatigue cracks [36] and also due to micro-cracking of the polymer surface because of intensive contact, mechanical and thermal effects [22]. The fatigue cracks start below the surface at a point where the shear stress is maximum. It is the interfacial layer properties that are related to fatigue wear. For more rounded asperities which do not cause stresses in the polymer large enough to cause cutting, many stress cycles (repeated traversals) are required to produce wear particles. Fatigue wear is usually associated with the contact stress, deformation, surface coverage of particle, and fatigue resistance, each of which depends on material, geometric, and process parameters [37].

2. 1. 4. DELAMINATION WEAR:

From the delamination theory of sliding wear [38], damage can result from cyclic shear deformation due to surface traction exerted by asperities leading to initiation and propagation of subsurface fatigue cracks. The softer surface experiences cyclic loading when the asperities of the harder surface plough into it. The resultant cyclic plastic shear deformation leads to subsurface crack initiation in the softer material, which on further deformation, leads to crack propagation and coalescence parallel to the surface. Long, thin delaminated wear sheets of material are removed when cracks shear near the surface.

Suh [39] extended the delamination theory of wear to polymers, according to which, when polymers slide against a surface, the surface layer will undergo shear deformation parallel to the surface along the sliding direction. When the force of adhesion and/or mechanical interlocking between the polymer and the sliding surface is strong enough and the applied stress are greater than the cohesive force, transfer of films occurs.

2. 1. 5. OTHER TYPES OF WEAR:

Wear can be considered as surface fracture due to accumulated damage in the surface and subsurface [40]. Subsurface failure of polymers can occur in the absence of adhesion or abrasion due to degradation as a result of frictional heating. This can cause localized polymer decomposition resulting in the loss of polymer material from the parent body. Due to the loss of visco-elastic properties in the polymer subsurface material, softening can occur and a fragment can be subsequently detached. This is a form of wear which is not found in metals, alloys or ceramics [41].

2. 2. FACTORS INFLUENCING THE WEAR OF POLYMERS

The nature and extent of wear in polymers is determined by the nature of the materials, the surface and bulk mechanical, physical and chemical properties of the frictionally interacting bodies, the operating parameters, the macro and micro-geometry, and the working environment. Polymers are sensitive to the influence of numerous factors caused by the effects of sliding interaction and external medium. The results of the wear investigations by Rymuza [42] show that the wear dynamics of polymer-polymer and polymer-metal systems are determined by properties of the polymer material such as surface energy, modulus of elasticity, specific heat, thermal conductivity, and operating conditions. The various factors which influence the wear of polymers are discussed below.

2. 2. 1. LOAD / PRESSURE:

The tribological behaviour of polymer materials depends on the applied normal load. It is known that the surface deformation depends on the applied load and with consequential changes in the mechanism of friction and wear. It has been found during the sliding of polymers that the amount of wear increases with increasing load [43,44].

Contact pressure raises the temperature of various visco-elastic transitions in the polymer. At low pressures where the heating due to friction is small, the wear rate of polymers is proportional to the applied pressure. At higher pressures the wear rate increases abruptly and is no longer proportional to applied pressure. This is possibly due to thermal effects at the interface which are high enough to cause melting or softening of the sliding polymer surface [9,24,45].

2. 2. 2. SPEED / TEMPERATURE:

The basic effect of speed is to increase the wear of polymers [46-48] in cases of metal-polymer systems due to an increase in the mean surface temperature generated at the points of rubbing contact. During sliding, physical and surface morphological changes occur due to high local stresses modifying the sliding contact characteristics which in turn influences the wear rate [49-52]. At higher speeds the wear rate reduces slightly due to surface melting and thermal softening caused by the high temperatures generated at the interface [53-55]. Briscoe et al. [56] have reported that some polymers at low speeds can exhibit a low friction and material transfer, whereas at higher speeds, the same material exhibits higher friction and susceptibility to transfer. The thickness of the film depends on the sliding speed, and it alters the interface geometry and the stability of the transfer film [57,58].

The frictional heat associated with sliding or rubbing can cause localized polymer decomposition resulting in a loss of polymer material from the parent body. The relationships between temperature and friction or wear are not simple as they also depend on other parameters. Interface temperature as a dependent variable in sliding tests is seldom used due to the complex interactions between parameters which have made it rather difficult to deduce the effect of temperature on the results.

2. 2. 3. DURATION OF TEST / SLIDING TIME:

During initial periods of sliding, the wear will be very high when the polymer is in contact with the virgin counterface. With the passage of time, the polymer transfers on to the metal counterface forming a thin layer of polymer material modifying the surface topography. This causes the wear process to change which may result in the reduction of the wear rate. But in contrast, as sliding time increases, sliding length also increases which in turn increases the contact temperature leading to higher wear.

2. 2. 4. COUNTERFACE ROUGHNESS:

The roughness of a surface is defined as any departure of the actual surface height from the ideal datum level, also known as the nominal or desired level. Knowledge of the prior nature of the surfaces is very important in understanding the mode of interfacial interaction between moving parts. The prior surface of the contacting bodies continues to change as a result of deformation and wear. Different wear mechanisms and wear rates have been observed by Tanaka and others [59] at varying degrees of roughness. Surface profile characteristics play an important role in an understanding of the mechanism of friction and wear of polymers [23,60] and among the many factors governing this, counterface roughness is likely to be of primary significance [61,62]. According to Maugis [25], wear rate increased when the surface became smoother and softer due to mechanical or thermal action. But higher roughness of the metal counterface produced predominantly abrasive wear on soft polymers as asperities acted as cutting tools, while a smooth surface favoured adhesive transfer. Hollander and Lancaster [62] have described two important processes that occur during sliding as transfer to the counterface and polishing of the counterface. This reduced the effective roughness of the counterface and localized asperity stresses which in turn reduced the wear.

Lancaster [30] has observed with polymers that when freshly prepared surfaces first begin to slide, the wear rate is initially high and ultimately decreases to a lower steady state value. It is concluded that the greater the initial roughness of the metal, the greater will be the volume of surface depressions to be filled. With increasing roughness there is a marked increase in the volume of polymer removed during the early stages of sliding before the wear rate reaches its steady state value. The limiting wear rate attained after the formation of the transfer films is not only dependent on the initial counterface roughness but also depends upon the apparent contact area. Jain and Bahadur [63] found that the area of real contact between the sliding surfaces is responsible for surface topography modifications governed by the shape, size and distribution of asperities, properties of the contacting surfaces, normal load and sliding speed conditions under which the contact occurs.

Eiss and Milloy [33] found that the steady state wear rates for polymers decreases with a decrease in roughness, average peak curvature and average penetration depth. Many researchers [64-66] have found that there is an optimum surface finish to give a minimum dry wear rate and the counterface roughness affects the type of transfer film laid down, thus controlling the wear process. Wear of polymer based materials have shown considerably higher dependence on the roughness of the counterface than their metallic counterparts. The tribological behaviour of metal-polymer pairs have been found to depend significantly on the radius of curvature of the peaks [67]. SEM photographs of the profile of the surfaces have revealed that there is a significant difference in the way in which polymer is deposited on the surface as a function of the surface roughness. Eiss and Bayraktaroglu [68] have found the amount of transfer to the surface is a function of the interaction between the roughness and the direction of sliding relative to the machine lay. The polymer wear process is also found to be dominated by the build up of a transfer film on the counterface because of changes in the topography of the counterface. During unlubricated sliding, the transfer of polymeric material is either beneficial or detrimental to the wear behaviour due to the topographical changes in the counterface. With prolonged sliding, as the thickness of the polymer film transferred increases and fills up the depressions in the counterface, it results in a polymer/polymer interaction.

2. 2. 5. PHYSICAL PROPERTIES:

Wear of polymers are influenced by fracture energy and surface energy. These properties are considered to have a significant effect in determining junction formation and polymer transfer [69]. The chemical composition and the thermodynamic concepts like surface and interfacial energies of the polymer affects the phenomena of adhesion [70,71]. Surface energy is the specific internal energy which is the change in the free energy of the surface associated with a unit increase of contact surface area [72,73]. Solids having high surface energy or high critical surface tension have high energy surfaces and exhibit a higher coefficient of friction as opposed to solids of low surface energy [71]. Rymuza [74] observed that an increase in surface energy of rubbing materials results in a degradation of the tribological properties. Jain and Bahadur [75] confirmed that a polymer of low surface energy tends to transfer to that of high surface energy.

The influence of adhesion decreases with increasing surface roughness and elastic modulus but with decreasing surface energy. The friction and wear of polymers involve time and temperature dependent properties related to their visco-elastic behaviour. The coefficient of friction and wear intensity are generally lower when sliding occurs parallel rather than perpendicular to the direction of alignment of machine lay. Maugis [25] has shown that the type of contact can be expected to have a considerable influence on the tribological behaviour of sliding solids. Hu and Eiss [76,77] have found that an increase in molecular weight results in a decrease in wear rate.

2. 2. 6. MECHANICAL PROPERTIES:

Friction and wear are affected by the mechanical properties of the polymer [60,78]. Depending on the morphology and/or crystallinity, the mechanical properties of polymers such as hardness, yield stress and elastic modulus show a marked change at the glass transition temperatures and decrease as the temperature increases, resulting in higher wear rates. The effect of hardness of the wearing materials can depend on the operating conditions. Therefore, the wear intensity may decrease or increase or be unaffected by the hardness of the materials in contact. Lee [24] observed that the thickness of the transferred polymer layer increased during sliding, which indicated that polymer wear can occur even on the transferred layer of a similar polymer. This led to the confirmation that the bonding between the worn material and the counterface is due to mechanical interlocking. Lancaster [79] found that the mechanical properties of polymers such as elastic modulus, hardness, tensile strength, elongation to break, etc., at various temperatures influenced the wear rates of polymers against metal counterfaces. The mechanical properties decreased with increasing temperatures resulting in minimum wear resistance. Both mechanical stresses and thermal effects play a role in the mechanism of failure of polymers. Wannop and Archard [80] observed catastrophic wear of the polymer surface where a large lump of polymer material was removed as debris, but the metal surface did not show this sign under similar conditions of sliding.

2. 2. 7. THERMAL PROPERTIES:

The physical state of the polymer is important for the tribological behaviour of polymer-metal sliding couples [81], and thermal decomposition and oxidation could eventually degrade the sliding surface to the point of failure [82]. Poor thermal conductivity and low specific heat of polymers results in high surface temperatures and reduced strength making them easily deformable at high temperatures [7], thus making them inappropriate for use at relatively high speeds or under high load conditions. During low temperature operation, polymers behave as low friction and wear resistant materials without much influence of the thermal properties. Surface melting of plastics due to frictional heat generated during sliding must be considered in view of the relatively low melting points and heat conductivities of polymeric materials.

2. 2. 8. LUBRICATION:

The mechanism of interface lubrication of polymers is complex [22]. With polymeric materials, the lubricant layer consists of long chain molecules not markedly different from the underlying polymer. In the case of a metal/metal pair, the reason for reduced friction or wear arises from the fact that the shear strength of the lubricant film is considerably less than that of the underlying metals [49]. Consequently for polymers, even if a strongly adsorbed film is formed, its shear strength can not be greatly different from that of the polymer itself. Though the effects of lubricant on polymer wear is usually to reduce wear, sometimes wear will be increased by a lubricant. There are other situations in which wear may remain unchanged or where the type of wear mechanism is changed but not the amount of wear [83]. There are number of ways in which a lubricant can increase wear or change it to a more undesirable form. These are by a change from mild to severe wear in a two-body wear situation, by being itself degraded to a harmful form, by chemical attack, or by trapping abrasive particles [7] and forming an abrasive slurry.

Absorption of organic molecules from the surface into the bulk plasticization results in deleterious effects of stress scouring and/or cracking on the wear of polymers. Many researchers [70,83-86] have found that fluids increase the rate of wear as they inhibit the transfer film responsible for low wear in dry conditions. When a lubricant is applied to a polymer, the lubricant molecules can penetrate it and alter its mechanical properties near the surface. Cohen and Tabor [87] have found that lubrication on polymers is less effective than that of metals because the film absorbed on the surface of the polymer is not as concentrated as that on metal.

2. 2. 9. HUMIDITY AND ENVIRONMENT:

Although wear is usually thought of as a mechanical process, it is foremost a study of surfaces in contact, whose characteristics may be altered by the nature of the operating environment. Changes in environment play a significant role by affecting the polymer film transfer to the counterface. It has been shown that the atmospheric environment and the amount of moisture influences the wear characteristics [88] and the wear begins with severe wear state and changes gradually to a steady state wear [89].

2. 2. 10. OTHERS:

Dowson et al. [90] have shown that counterface imperfections can cause a severe effect on the wear of polymers. Interruption in the sliding of polymer/metal pairs has a significant effect of increasing the wear rate as new running-in takes place every time the phenomena is restarted. The cleanliness of the substance is important in determining the amount of transfer. Contaminants might be beneficial like surface films, inhibiting adhesion or detrimental like abrasives as observed by Lipson [91]. Dickens et al. [92] found that the friction and wear rates of polymers depends on the geometrical sliding configuration.

2. 3. FRICTION OF POLYMERS

The differences between metallic and polymeric friction are due to the differences in the elastic-plastic response of metals and the visco-elastic response of polymers. The softness of polymers often allows transfer of material to the mating surface. In such cases, the coefficient of friction tends towards the value for polymer on polymer, even where the surface in contact with the polymer is metallic.

Polymer sliding friction depends on sliding velocity [93-96] and the coefficient of friction has been found to decrease with contact pressure. Lancaster [28] has reported that there are two main processes involved in friction, (i) the ploughing of asperities of the harder solid through the surface of the softer and (ii) the shearing of the adhesive bonds formed at the region of contact. Uetz et al. [97] observed that the friction and wear rate of polymers are strongly determined by their visco-elastic behaviour and therefore one should expect the coefficient of friction to depend on the time of loading [49]. Increasing the counterface roughness has been found to reduce the coefficient of friction over a range of loads [22]. Because of the transfer of a polymer to a hard smooth counterface during sliding, friction is attributed to the shear strength of the polymer. Temperature is also known to affect the material behaviour of the polymer which, in turn, affects the friction and wear mechanism. In addition, the coefficient of friction of polymers is dependent to some extent on the value of the load and geometry [87].

It has been shown that the physical and mechanical behaviours of the polymeric materials influence the friction of polymers [78,98,99]. Pooley and Tabor [100] observed that the coefficient of friction accompanied by material transfer is affected by the molecular structure and strength of polymers. The temperature in the contact zone, visco-elastic behaviour under load, chemical activity of the environment [101], sliding velocity, surface roughness and hardness [102] influence the friction of polymers. Dowson [103] has found the surfaces which are subjected to high strains in the sliding process influence the friction.

The relationship of polymer ductility to transfer influence the degree to which the polymer friction depends on roughness. Experiments conducted by Eiss [104] have indicated that the friction decreases with increasing roughness or stays the same or increases slightly with increasing roughness. As transfer occurs, the topography becomes modified which may be responsible for the relative uncertainty in the coefficient of friction with surface roughness. Friction of polymers is found to be quantitatively related to adhesion and there is an exponential relationship between coefficient of friction and surface energy [105,106]. It has been found that the coefficient of friction increases fairly regularly with the surface energy.

An optimum combination of the two properties of friction and wear is desirable for many applications. This is difficult to achieve because weak intermolecular bonds are the pre-requisite for a low surface energy and low friction. Strong bonds are required for high cohesion in the interior and high wear resistance. The frictional force is associated with the expenditure of energy in the contact region and it is the process of energy dissipation which may lead to the eventual wearing of the polymer. Though both friction and wear are the result of surface interaction, in practice there is often little correlation between the two [78]. The transfer of the polymer to the counterface attributes friction to the shear strength of the polymer, which is also one of the main reasons for wear. From the delamination theory of wear developed by Suh [39], the coefficient of friction has a significant effect on the wear process. When the wear particles are removed, the coefficient of friction decreases and it eventually reaches a steady state value when the sliding is resumed after the removal of wear particles.

2. 4. SYNOPSIS

The specific nature and the structural transformations occurring during sliding determine the mechanism by which polymer-polymer and metal-polymer pairs wear. Each new combination of interacting materials possesses its own features. Polymers exhibit peculiar features in the course of frictional interaction with metals.

The main tribological properties for polymers are the load carrying capacity with minimum deformation, low coefficient of friction and high wear resistance. These properties are interrelated and for design purposes an in-depth testing should be carried out to establish the influence of these factors. Despite extensive research in the field of wear of polymers, there is no general agreement on the wear processes and various factors influencing the polymer-metal interaction.

The major tasks in the study of wear are the quantitative prediction of friction and wear behaviour of solids based on the relationship between surface traction, temperature, operating variables, material properties, and the wear mechanism. For a given system, it is necessary to know all the forms of wear present and the conditions under which they occur. Mathematical modelling is crucial to engineering design, as it provides a means of comparing competing designs and assessing the effects of different materials, dimensions etc., without engaging in extensive and expensive prototype testing.

The wear relationships, which are based on either experimental observations or theoretical assumptions, can be used to explain the influence of several factors on the wear phenomena. The wear equation analyzes the contribution and effects of individual factors, and can be used to evaluate the importance of these factors that influence the wear process. The wear equation can also be used to determine a proportionality wear coefficient for a particular combination of a sliding pair under given operating conditions.

The next chapter deals with the history and development of an analytical equation for the wear of polymers.

3. DEVELOPMENT OF THE WEAR EQUATION

3. 1. PREVIOUS ANALYSIS OF THE WEAR EQUATIONS

In 1952 Burwell and Strang [107] found that the wear volume of a metal pin, under steady-state conditions at light loads, was proportional to the load and the length of path traversed, so that

$$V = kLW\ , \qquad \text{where,}$$

V = volume of worn material, k = wear constant,
L = sliding length, W = normal load.

In 1964 Ratner et al. [108] were the first researchers to develop a general equation for the wear of polymers. Due to the specific nature of polymers, it was proposed to relate the wear of polymers with their material properties of strength and elongation to failure;

$$\frac{V}{L} \propto \frac{\mu}{H \sigma \varepsilon}\ , \qquad \text{where,}$$

μ = sliding coefficient of friction, H = indentation hardness,
σ = fracture or breaking strength, ε = elongation to fracture or break of the polymer.

The comparison of the prediction of this equation with experimental data was necessarily qualitative. Analysis was complicated due to temperature effects on the mechanical properties of polymers. This relationship was drawn from the most general considerations, without a detailed investigation of the mechanism of breakdown of the surface layer and separation of the particles, and showed the part played by the mechanical characteristics of a material in determining its resistance to wear.

In 1964 Lewis [109] directly applied a correlation for the wear of polymers by relating the wear of a polymer surface to operating parameters such as load, sliding velocity and time. He proposed the following relationship for the unlubricated wear of a polymer surface.

$$V = kWvT\,, \qquad \text{where,}$$

v = sliding speed, T = time.

The purpose of this equation was to show that relatively simple tests could form the basis for wear prediction and evaluation of pressure-velocity (Pv) limits for polymers in bearings, piston rings and seals. The equation did not take into account the surface changes in the contacting surfaces, surface roughness, hardness, geometrical factors, thermal factors, or type of application.

In 1965 Rabinowicz [110] developed an equation for adhesive wear by assuming that each junction remains in existence during an effective working distance after which it is broken and its load carrying capacity is taken up by a new junction which will be formed. Based on the probability 'k' that any junction leads to the formation of a transferred fragment and the assumption that such a wear fragment is a hemisphere, the volume of transferred fragments formed in sliding a distance L was determined as

$$V = \frac{kWL}{3p_m}\,, \qquad \text{where,}$$

p_m = flow pressure of the softer of the two surfaces.

In 1970 Rhee [111] proposed a wear equation for the wear of polymers to be an exponential function of load, speed and time. The reason for the development of this relation was, when the equation proposed by Lewis [109] was used to express the wear of teflon matrix bearing materials, the wear coefficient was found to vary by a factor of two with respect to that found by Lewis. It was found less than satisfactory for correlating the wear with loads, speeds and times. Hence Rhee proposed the equation as

$$\Delta w = k\,W^{a}\,v^{b}\,T^{c}\,, \qquad \text{where,}$$

Δw = weight lost, $\{a, b, c\}$ = a set of parameters.

This wear equation was found to be satisfactory for the wear of polymer matrix friction materials but it did not consider the polymer material properties.

Numerous attempts have been made to categorize the various types of wear which can occur. There is no standardization for any type of wear other than abrasive wear.

In 1972 Lancaster [28] developed a simple theory of abrasive wear based on the model developed by Ratner et al. [108], by assuming that a hard conical asperity indents a softer material and ploughs or cuts a groove during sliding. The constant 'k' expressed the fact that only a portion of the material in the groove would be removed as debris.

$$V = k\frac{WL\tan\delta}{\pi H}, \qquad \text{where,}$$

δ = angle of slope of the cone.

This equation was in agreement with the fact that abrasive wear of polymers is proportional to the applied load but the effect of counterface roughness (c.l.a. proportional to $\tan^2\delta$ in the above equation) was found to be different from that predicted. From the experiments conducted, it was unreasonable to expect a relationship between the wear of polymers against surfaces of different roughnesses and a predominantly plastic parameter such as the indentation hardness. This was because with polymers there is no unique mode of deformation. Therefore, the resulting equation was found to be generally invalid for polymers over some of the ranges of roughnesses tested.

Since there was no generally accepted equation available for the prediction of wear of polymers, in 1974 Kar and Bahadur [9] developed a wear equation using dimensional analysis based on experimental data for adhesive wear of polyoxy methylene (POM) and 20% PTFE filled POM. The objective was to consider those variables which dominate the wear process at a polymer-metal sliding interface and to express them in the form of an equation to determine a wear constant. The wear equation was in terms of the sliding variables, pressure(P), speed(v) and time(T), and material properties, modulus of elasticity(E), surface energy(γ), thermal conductivity(K) and specific heat(C_p). The wear volume was found to be

$$V = k\, P^x\, v^{(y-z)}\, T^y\, \gamma^{(3-y+z)}\, E^{(-3-x+y)} \left(\frac{C_p}{K}\right)^z$$

where x, y, and z, are the exponents to be determined experimentally.

This wear equation was developed specifically for the above materials but the model could be extended to other materials and it did not consider the effect of counterface materials in the determination of the dimensionless wear constant.

In 1978 Atkinson et al. [19] evaluated the wear rate of a polymer as the ratio of the slope of any straight line portion of the graph of the volume of polymer lost vs. sliding length and the normal load.

$$\text{wear rate} = \frac{V}{W\,L} .$$

The wear factors were evaluated using the above relationship and the results were used to analyze different wear processes. Under the conditions tested, the wear rates were independent of the applied load and dependent on counterface roughness in a complex manner indicating that initial counterface roughness is an important feature in the wear process. It was found that variation in the nominal stress had no effect on the wear rate of the polymer. There were some difficulties in analyzing the effect of temperature, counterface roughness, and erratic wear behaviour during initial wear process for some test conditions.

In 1978 Jahanmir [112] developed a general wear equation assuming that an energy analysis might be a useful tool in identifying the fundamental mechanisms of wear. Based on the similarities of the basic wear mechanisms and experimental observations, he proposed a general wear equation in which the volume of material worn is inversely proportional to the specific wear energy (the amount of energy expended for wear of one unit volume of material). The specific wear energy is composed of a number of components like plastic strain energy, surface energy, cutting energy and ploughing energy. The contribution of each component to the specific wear energy was dependent on the wear mechanism. The wear relation in terms of material properties used in developing the equation based on energy analysis was

$$V = \frac{k\,W\,L}{C\,H} , \qquad \text{where,}$$

C = geometrical constant (= 1 for abrasion, = 3 for adhesion).

Jahanmir assumed that since hardness and the wear constant depend on the microstructure of materials, they should not appear independently in the wear equation. Therefore, the equation can be rewritten as, $V = k\ W\ L$. Jahanmir concluded that though an energy analysis appeared to be a useful tool in understanding the wear mechanism it was very approximate due to complexities involved during the interaction of several wear mechanisms responsible for wear particle formation.

In 1978 Eiss et al. [113] described a model for predicting the transfer of polymer to rough hard surfaces. The model used the normal load, yield strength, the apparent area of contact, the bearing area curve for the surface, the density and the shear angle. The model assumed that the abraded polymer was transferred to the metal surface and was in the vicinity of the asperities and the volume was expressed as

$$\frac{V}{L} = \sum_{i=1}^{n} \frac{p_i^2\, D}{2\ L\ \tan\phi}\ , \qquad \text{where,}$$

p_i = penetrating depth, ϕ = polymer shear angle, D = width of the slider,
n = number of asperities penetrating the polymer over a sample length.

Though the experimental observations correlated with the model, the asperity slopes predicted were larger than those measured on steel surfaces. The critical penetration depth was also larger than what actually existed. The model was sensitive to changes in shear angle at small values leading to an uncertainty associated with the transfer of the polymer. It could not be used for random surfaces which had no machine surface lay because of the above uncertainty in the transfer of the polymer.

In 1987 Dowson et al. [90] determined the wear factors for polymers according to the following relationship,

$$V = kWL\ .$$

The wear factors evaluated at approximately the same counterface roughness from this simple relationship did not correlate with the wear factors obtained from an earlier equation developed by Dowson et al. [65] as '$k = 4.0 \times 10^{-5}\ (Ra)^{1.2}$' {where Ra is the c.l.a. roughness} using the same relationship. This discrepancy was due to scratches of various depths and geometrical features of the counterface imperfections causing changes in wear behaviour. For this reason, this relation could not be used for general application purposes.

3. 2. THE PROPOSED WEAR EQUATION

The above review of the wear models that have been proposed show considerable variation. Though some of these equations were developed from experimental results and others were based on a theoretical analysis, neither approach has led to an equation which can be used for all metal-polymer sliding pairs. Regardless of the approach taken, it appears that a generalized wear equation may not evolve based on limited experimental results or assuming a single wear model or process.

None of the wear models discussed in Section 3.1 incorporate the effect of counterface material or its roughness. Except for the equation developed by Kar and Bahadur [9] most of the wear equations reported here have related the volume loss to the operating variables through a wear constant or a wear coefficient. All the uncertainties in other variables are hidden in the wear constant or coefficient 'k' as expressed by these equations. Therefore, 'k' is a complex combination of all the uncertainties of the influence of various factors on the wear phenomena and it is unable to describe the sensitivity of the equation to these individual factors. It has been already discussed that along with the operating variables such as load, sliding speed and duration of sliding, counterface roughness is also an important operating variable influencing the wear of polymers. Therefore, it is intended to develop an empirical wear equation comprising most of the factors involving both operating variables and material properties known to influence the wear of polymers.

Development of an empirical model necessitates the introduction of mathematical operations on observations. The concept of dimensional analysis defines in an explicit fashion the operations on measurement results or on the set of dimensional quantities. Application of dimensional analysis to any practical problem is based on the hypothesis that the solution of the problem is expressible by means of a dimensionally homogeneous equation in terms of specified variables. The purpose of dimensional analysis is to give certain information about the relations which hold between the measurable quantities associated with various phenomena. The final purpose of the investigation is to develop a general method of setting up the variables which are characteristic of each process. Thus, dimensional analysis can be used to characterize a phenomenon in terms of the relationships among dimensionless variables, fewer in number than the original physical variables. It also helps to predict the qualitative form of the mathematical relationship.

Similarity laws have proven to be satisfactory when applied to engineering processes. In wear investigations, the qualitative statements are of interest because wear is not an intrinsic material property, rather it depends on physical quantities or variables. Due to several factors involved in the wear process, complicated relationships occur between individual factors governing the wear process. This makes it difficult to correctly assess the applicability of the test results. Dimensional analysis of the factors influencing the wear process may be expected to provide a characteristic expression.

3. 2. 1. FACTORS CONSIDERED IN THE DEVELOPMENT OF THE MODEL:

The factors that are considered in developing the proposed wear equation are the dependent wear volume, operating variables such as load, sliding speed, duration of test, counterface roughness, mechanical property (modulus of elasticity), physical property (surface energy) and thermal properties (thermal conductivity and specific heat). From the review of the literature it is observed that the above factors have been used to describe the wear process and are explained in the following detail.

(i) Normal Load (W):

In any contact of two solid bodies under normal load, only a few isolated spots come into contact where junctions are formed. The contact junctions formed at a few asperities take up the entire normal load acting on the surface. Pressure is not an ideal operating variable as the area of the pin surface considered in finding the pressure is not the true contact area. Due to these uncertainties, and from a review of wear problems described in the literature, where mostly normal load has been used as the operating variable, load is considered to be a more appropriate operating variable.

(ii) Sliding Speed (v) and Duration of Test (T):

Both sliding speed and duration of test are separately considered as individual operating variables instead of the single variable sliding length, which is the product of these two variables. Varying wear phenomena are observed as time progresses during sliding, for example from running-in wear, to mild wear, to steady-state wear, to severe or extreme wear conditions. Sliding length is not a suitable single replacement for two independent variables speed and time because it does not represent the breakdown effect of speed and time individually. The same sliding length can be obtained by varying either speed or time or both. Because both sliding speed and duration have their own influence on the wear behaviour, they have been considered as two independent operating variables. However, it is acknowledged that sliding length is frequently used in the literature for comparison of results.

(iii) Counterface Roughness (α):

Counterface roughness has not been considered in most of the wear models reviewed. The models which ignored counterface roughness assumed that the transfer layer was quickly established, thus eliminating the effect of counterface roughness on any further influence on the wear process. From the experimental observations conducted in this research it was clearly seen that counterface roughness played a major role in the wear behaviour of polymers. Counterface roughness also affects the coefficient of friction in a sliding process. The contact junctions resulting in wear debris primarily depend on the type of surface profile of the counterface. Due to its prime role in the wear process, counterface roughness is considered to be an important operating variable.

(iv) Surface Energy (γ):

Surface energy is a measure of the total energy associated with a unit increase of surface area in contact. It represents work of adhesion, cohesion and deformation. Surface energy is responsible for junction formation, molecular interaction and cohesive strength, all of which play an important role in the wear of polymers.

(v) Modulus of Elasticity (E):

Modulus of elasticity is the mechanical property of a material that determines the stress-strain relationship. During the wear process the material undergoes mechanical deformation. Since wear is a result of shearing of asperity junctions under load, stress-strain relationships are very important in determining the process of mechanical failure of these junctions during sliding. From a review of the literature of the wear of polymers it is seen that the modulus of elasticity has been used in many cases. Since polymers are visco-elastics possessing stress-strain behaviours not found in traditional materials, modulus of elasticity is considered a factor influencing the wear of polymers.

(vi) Specific Heat (C_p) and Thermal Conductivity (K):

Specific heat and thermal conductivity are thermal properties of a material. The temperature generated at the sliding contact is important as polymers possess low glass transition temperatures. Polymers are poor conductors of heat, and the temperature at the contact affects the properties of the polymer which in turn influences the wear phenomena. Therefore, to accommodate the temperature effects and influence of thermal properties during wear of polymers, these material properties are considered.

3. 2. 2. DEVELOPMENT AND SIGNIFICANCE OF THE WEAR EQUATION

To carry out the dimensional analysis, the approach used by Kar and Bahadur [9] has been used. The main dependent variable is wear volume. Sliding velocity, modulus of elasticity, surface energy and thermal conductivity are used as repeating variables. The four primary dimensions are mass(M), length(L), time(T) and temperature(Θ). The dependent variable wear volume V is grouped and expressed as

$$\Psi\,(V, W, T, \alpha, C_p, \gamma, E, v, K) = 0 \qquad 3.1$$

where Ψ is some arbitrary function.

Using the Buckingham Pi theorem [114,115], the following five dimensionless groups were obtained after a detailed analysis (given in Appendix 2). The dimensional analysis provided a base for developing the wear equation by reducing the number of variables from nine to five dimensionless groups,

$$\left(\frac{V\,E^3}{\gamma^3}\right),\ \left(\frac{W\,E}{\gamma^2}\right),\ \left(\frac{v\,T\,E}{\gamma}\right),\ \left(\frac{\alpha\,E}{\gamma}\right),\ \left(\frac{C_p\,\gamma}{v\,K}\right).$$

The physical significance of each of these groups is explained as follows;

$\frac{VE^3}{\gamma^3}$: This is the dependent group since it contains the wear volume as a dependent variable. It includes the modulus of elasticity which is involved in the deformation process. Surface energy determines the work of adhesion responsible for junction formation and interface strength. This group represents the significance of interface contact and deformation leading to material loss.

$\frac{WE}{\gamma^2}$: This group involves normal load which is one of the operating variables which, along with the modulus of elasticity, is responsible for junction growth and deformation under load. Surface energy contributes to interface junction strength. The group can be split as $(W/\gamma)(E/\gamma)$, which represents the influence of normal load on interface contact, junction formation and its strength characteristics.

$\frac{vTE}{\gamma}$ or $\left\{\frac{TEC_p}{K}\right\}$: In this group the speed and duration of a test combine to give sliding distance during the wear process. Along with modulus of elasticity and surface energy, this group represents the distance over which the phenomenon of formation and deformation of junctions occur. By combining the groups $\{vTE/\gamma\}$ and $\{C_p\gamma/vK\}$, a new group $\{TEC_p/K\}$ is obtained, which has duration of test as the only operating variable. This group confirms the fact that with an increase in time, a variation in temperature and thermal factor (C_p/K) will occur, which can affect the modulus of elasticity. Overall, this group determines the process and duration of interface formation and deformation with thermal effects.

$\frac{\alpha E}{\gamma}$: Of the counterface characteristics, counterface roughness is the only parameter considered. This determines the participation of asperity distribution, asperity height and characteristics of the surface profile during formation and deformation of asperity junctions. It is assumed that counterface roughness plays an important role in the wear process as it determines the apparent contact area which supports the load and is responsible for the type of wear process that occurs.

$\frac{\gamma C_p}{v K}$: The ratio (C_p/K) is a factor controlling the thermal contribution during interface formation and that the thermal influence during this process is due to speed. The group is rewritten as $\{vK/\gamma C_p\}$ to represent velocity as a prime variable. Thermal properties control the wear as transfer films and material properties are affected by the contact softening temperature.

Redefining Equation 3.1 by combining all the groups, it follows that

$$\Psi\left(\frac{VE^3}{\gamma^3}, \frac{WE}{\gamma^2}, \frac{vK}{\gamma C_p}, \frac{TEC_p}{K}, \frac{\alpha E}{\gamma}\right) = 0 . \qquad 3.2$$

An analysis of the application of dimensional analysis in wear problems was carried out. From the theory of dimensional analysis, the main dependent group $\{VE^3/\gamma^3\}$ was expressed in terms of the undetermined function Ψ comprising the other four groups. The undetermined function Ψ is evaluated from the experiments and then a relationship can be established between the main dependent variable 'V' volume of the worn polymer material and the variables influencing the wear of polymers. Equation 3.2 is rewritten as

$$\left(\frac{VE^3}{\gamma^3}\right) = \Psi\left(\frac{WE}{\gamma^2}, \frac{vK}{\gamma C_p}, \frac{TEC_p}{K}, \frac{\alpha E}{\gamma}\right) . \qquad 3.3$$

In Equation 3.3, the volume of material lost is explicitly expressed in terms of the operating variables (normal load, sliding speed, duration of test and counterface roughness) which can be controlled during the experiments, and material properties (modulus of elasticity, surface energy, specific heat, and thermal conductivity). To find the undetermined function Ψ in the above equation, a number of experiments were conducted by varying only one operating variable and maintaining the other variables the same. This was the same as controlling the dimensionless groups because each group had only one operating variable and the rest were material properties which are constant for a given polymer. From the test results, graphs were plotted for the volume of the material lost against operating variables on linear and logarithmic coordinates and best fit curves were explored to find which relationship was the most appropriate for each material combination (The graphs are presented in Appendix 3). The relationship used in plotting the results on linear coordinates for load as the operating variable was $V \propto W$, and for logarithmic coordinates was $V \alpha W^p$, which can be written as an equation as; '$\log V = \log G_1 + p \log W$', to justify the use of equation '$y = mx + c$', to find the exponents as slopes of the best fit straight line on logarithmic coordinates. The same relationship is used for all operating variables.

Since the undetermined function is determined to be either linear or exponential, the main dependent group with the wear volume in Equation 3.3 is expressed as being proportional to the other groups with operating variables as follows. For the linear relationship

$$\frac{VE^3}{\gamma^3} \propto \left(\frac{WE}{\gamma^2}\right)\left(\frac{vK}{\gamma C_p}\right)\left(\frac{TEC_p}{K}\right)\left(\frac{\alpha E}{\gamma}\right), \qquad 3.4a$$

and for the non-linear relationship

$$\frac{VE^3}{\gamma^3} \propto \left(\frac{WE}{\gamma^2}\right)^p \left(\frac{vK}{\gamma C_p}\right)^q \left(\frac{TEC_p}{K}\right)^r \left(\frac{\alpha E}{\gamma}\right)^s . \qquad 3.4b$$

The Equations 3.4a and 3.4b are simplified and the wear equations are written with k_w as a proportionality dimensionless wear coefficient for both relationships. For the linear relationship

$$V = \frac{k_w W v T \alpha}{\gamma} , \qquad 3.5a$$

and for the non-linear relationship

$$V = k_w W^p v^q T^r \alpha^s E^{(-3+p+r+s)} \gamma^{(3-2p-q-s)} (C_p/K)^{(r-q)} . \qquad 3.5b$$

The wear coefficients are found for each polymer by substituting the numerical values in the above equation. A wear equation for a particular polymer material is then written by replacing the wear coefficient by its numerical value.

After these wear equations were developed, the next task was to identify the appropriate relationship between the wear volume and the factors influencing the wear process. The next chapter deals with the statistical analysis of the experimental data, an evaluation of the wear coefficients developed for both linear and non-linear models, and an uncertainty and sensitivity analysis of these relationships.

4. EMPIRICAL MODELLING OF THE EQUATION FOR THE WEAR OF POLYMERS

4. 1. WEAR TESTING OBJECTIVES

Tribological data can be more easily obtained from simplified model tests than from costly field tests. Field tests are carried out over long periods and with sometimes inconclusive results because of the difficulty in controlling all the variables. Model tests may be designed to simulate the tribological interaction of the field equipment, but usually are of short durations. To accelerate the testing, usually the loads or velocities are increased.

Since wear in engineering components is a complex process involving many interrelated variables, it is to be expected that even for specific cases, a laboratory simulation is generally not straightforward. Different wear tests were conducted on a wear testing apparatus designed in the laboratory to model the wear of polymers and determine the wear coefficients. The wear results in conjunction with SEM photographs were used to study the wear processes, analyze the effect of operating variables, and evaluate the behaviour of different polymer materials.

4. 2. BACKGROUND TO THE EXPERIMENTS

There are no testing standards nor is there any standard testing machine for evaluating the wear of polymers. As a result, when the experimental program for this research was being planned, it was required to develop a testing apparatus for the wear of polymers. It was believed that the simplest and the most economical solution for a testing machine would be a pin-on-disk machine, which is the type used in many wear testing procedures. The machine allows uniform and controlled test conditions to be established and monitored. In a pin-on-disk machine the stationary pin specimen is loaded against a rotating counterface disk. It was decided to modify an existing sand abrasion tester designed for ASTM G-65. This was done by replacing the rubber wheel with a steel counterface. The configuration is known as a horizontal pin-on-disk machine, because the pin axis is horizontal with respect to the axis of rotation. After the modifications were complete, some preliminary tests were conducted with some polymers such as ryton, hular, teflon, and nylon used in oil industries for centralizers and coupling roller wheels on sucker rods.

From preliminary testing it was found that the rate of wear varied, depending on the testing plan, i.e., initial, mid term, long term. Other characteristics found during the preliminary tests were that higher roughness and higher loads caused increased wear, that an increase in duration of test resulted in more wear, and that counterface cooling was effective in reducing the wear volume and coefficient of friction, which had a greater influence than expected. Following a given test, no significant change in the counterface roughness centre line average (c.l.a.) value was found, but the profile of the surface topography was found to be different from that of the original profile. It was unexpected to find the c.l.a. remaining the same although the profile changed.

The objective of the research was to investigate and analyze the information obtained from these preliminary tests in greater detail. These tests formed the basis for the selection of different polymers and different operating ranges for further testing. The following ranges were chosen; load: 70 - 150N, speed: 0.125 - 0.625 m/s, sliding duration: 18000 - 90000 sec (but later it was noticed that teflon wore faster than expected and the duration range was reduced to 3000 - 9000 sec), and counterface roughness: 0.05-0.4 microns. Sliding duration was chosen to be a more appropriate independent variable than sliding length, which is derived from speed and duration. Sliding speed was already considered as a variable and hence by considering sliding length again, the analysis of the effect of duration was not possible. A review of the literature and mathematical model consider duration and sliding speed separately while analyzing the wear behaviour, though eventually the combined effect is represented as the effect of sliding length. The preliminary results also indicated better representation with sliding duration and the objective in the development of wear model was to include those independent variables that are believed to influence the wear behaviour.

The original horizontal pin-on-disk machine was modified with a smaller disk and a lever arm to measure the normal force and the tangential force between the polymer pin and the steel counterface by means of a load cell. On this machine each test was conducted with a freshly prepared counterface disk, thus controlling the counterface roughness. It was only possible to run the test at the same radius of the disk. This did not allow for testing of different radii of disks without using a separate disk for each radius. As it was more convenient to grind and polish new surfaces on the rim of the counterface, the major testing of six polymers to evaluate the validity of the theoretical model was conducted on this machine. Thus, the main objective of the tests conducted on the horizontal pin-on-disk machine, was to use the results obtained from six different polymers to develop a wear equation. Some tests were conducted to analyze and compare the wear and friction behaviour at various operating conditions for different polymer materials. During the tests, temperature at the sliding contact was controlled by convection with a cooling fan.

It was decided to build a vertical pin-on-disk machine to run parallel experiments to those conducted on the horizontal pin-on-disk machine to investigate the effect of sliding radii of the disk while maintaining constant surface sliding speed in addition to evaluation of the effect of other operating variables on the friction and wear behaviour of polymers. The results of this testing machine could not be used in the development of the model because it was difficult to conduct each test at the same sliding radius due to problems encountered in preparing the counterface owing to the complex design of the disk. In addition, the effect of sliding radius was also not known. Thus, the main objective of the tests conducted on the vertical pin-on-disk machine was to analyze the wear and friction behaviour at different sliding radii or disk speed in rpm, while maintaining the same surface sliding speed. The operating temperatures were controlled by conduction from cooling water circulating inside the copper coils beneath the counterface disk.

A description of both pin-on-disk machines is given in Appendix 1. As the following analysis in Chapter 5 will show, the results from each machine were generally comparable, although not exactly in every case. It was also recognized that the results from these two configurations need not be identical but that the relative behaviour of one polymer compared with other should be about the same.

4. 3. EXPERIMENT PROCEDURE IN BRIEF

Wear pins of various commercially available polymers were made by machining an extruded rod in the shape of a truncated cone shown in Figure 4.1. The relatively small surface area of 10-12 mm^2 caused the initial surface of the pin to be removed rapidly and further wear represented the bulk material loss. The conical form provided a large backup of material helpful in minimizing distortion under load. The counterface disks were made from AISI 1018 steel and heat treated and stress relieved (HTSR) 4140 steel.

The counterface disk was ground and polished prior to starting each test to obtain the required counterface roughness. The polymer pin was cleaned and weighed in an electronic balance to an accuracy of ±0.0001 grams and its mass was compared with a previously weighed standard polymer pin.

A fixed pin of polymer was loaded against a rotating steel disk. Different operating parameters such as load, speed, duration of test, and counterface roughness were chosen. During the test, the tangential force was plotted on a chart recorder. The coefficient of friction (c.o.f.) during the test was determined using these plots. After the test was completed the wear pin was removed and cleaned to remove all the wear debris, weighed, and its mass was compared with a standard pin. The wear volume was found by dividing the difference in mass of the polymer pin before and after the test from the density of the polymer. The tests were repeated three to four times for concurrency in results. A series of tests were conducted by varying one of the variables and keeping all the others same.

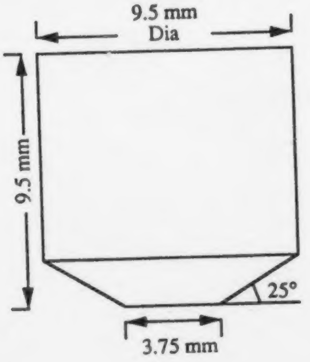


Fig. 4.1 : Shape and dimension of the polymer pin

4. 4. PRESENTATION AND DEVELOPMENT OF DATA

Data recorded on the horizontal pin-on-disk machine was used to plot the volume loss of polymer pin vs. the operating variable. From the test results it was seen that the difference in the volume loss of polymer when sliding against the two different counterfaces chosen was noticeable but did not vary significantly in their magnitude. Therefore, a single combined graph for volume loss against each operating variable with both counterfaces was sufficient to represent the relationship.

4. 4. 1. STATISTICAL ANALYSIS AND CONDITIONING OF TEST RESULTS:

A complete statistical analysis of the experimental data for the wear of all polymers used in developing the empirical model was carried out. A specific example of the statistical analysis of the data for the polymer - 'delrin' is shown in Appendix 3: Tables A.3.2(a) - A.3.2(d). The statistical analysis included the following:

1. The mean value '$\bar{X}$' of the wear volume from a minimum of three trials under identical operating conditions for each variation of operating variable.
2. The standard deviation 'σ_x' of the above set of data.
3. The standard deviation of the mean (SDOM) or (Standard Error or Standard Error of the Mean) - $\sigma_{\bar{x}}$: This is defined as $\sigma_{\bar{x}} = \sigma_x/\sqrt{n}$ (n - sample size, for this case n = 3), found for each data point, i.e., mean wear volume. This determines the standard error in the mean value of wear volume which was used in the graphs and analysis. The final wear volume is written as: $\bar{X}_{final} = \bar{X} \pm$ SDOM.
4. The percentage error is calculated from the above standard deviation of the mean and written as: % Error = $\sigma_{\bar{x}} / \bar{X}$. Thus the final wear volume is expressed as: $V_{final} = V_{\bar{x}} \pm$ % Error.
5. As a check point to the above analysis, the statistical conditioning of the experimental data was carried out. This was used to condition the experimental data in view of the possibility of an erroneous data point resulting from a measuring or recording mistake. If this data point appeared questionable when compared with the other data collected then a decision was made whether the deviation of the data point was due to a mistake (hence to be rejected) or due to some unusual but real condition (hence to be retained). A

statistical procedure known as Chauvenet's criterion provides a consistent basis for making this decision.

Application of Chauvenet's criterion requires computation of a deviation ratio DR for each data point, followed by comparison with the standard deviation ratio DR_0. The standard deviation DR_0 is a ratio that depends on the number of measurements, while the deviation ratio DR for a point is defined as

$$DR = \frac{x_i - \bar{x}}{\sigma_x} , \qquad 4.1$$

the data point is rejected when $DR > DR_0$, 4.2

and retained when $DR \leq DR_0$. 4.3

Values for the standard deviation ratio DR_0 are listed by Dally et al. [116].

If the statistical test of Equation 4.2 indicates that a single data point in a sequence of 'n' data points should be rejected, then the data point should be removed from the sample and the mean '$\bar{X}$' and the standard deviation 'σ_x' should be recalculated. Chauvenet's method can be applied only once to a given set of data. Using the above criterion it was found that the experimental data for volume loss of polymers were within the limits of experimental error. No data points were rejected based on Chauvenet's criterion of statistical conditioning of data.

Following the statistical analysis (presented in Appendix 3 in Tables A.3.3 - A.3.14) various graphs of volume loss of each polymer against both counterfaces for each set of tests were plotted both on linear and logarithmic coordinates (Figures A.3.1 to A.3.6 and A.3.7 - A.3.12, in Appendix 3). These graphs have been separately plotted for volume loss under different operating conditions for six different polymers (delrin, high density polyethylene (HDPE), polyvinyl chloride (PVC), rulon, teflon(m) and teflon(v)) against both steel counterfaces. From regression analysis the data points from each set of tests were best fit on to a straight line. Thus, the best fit straight line in all these plots yielding the highest regression coefficient was for an exponential relationship between volume loss and the different operating variables.

The scatter in the experimental results with tests conducted under identical operating conditions can be seen from Figures A.3.1 - A.3.12. Since humidity can affect the test results, an analysis of humidity recorded for all tests was carried out. Each set of tests for repeatability were conducted approximately at the same humidity, as they were all conducted on the same day. However, for a given polymer-steel combination under different operating variables, tests were conducted in the humidity range of ±5% of the mean value. Therefore, the scatter in the experimental results are attributed to other uncertainties in conducting the experiment and believed not to be the result of minor changes in humidity.

On the basis of the regression analysis it was deemed more appropriate to base the empirical model on the non-linear fit of the data. The exponents were equal to unity with operating variables in the case of linear relationship and were other than unity in the case of non-linear relationship. Therefore if the linear relationship was valid, then the exponents in the case of non-linear relationship should have been equal to unity as linearity is a special case of non-linearity explained as below.

$V \propto$ (operating variables), for linear relationship,

$V \propto$ (operating variables)^i, here i is an exponent, for non-linear relationship.

If $i = 1$, then the non-linear relationship reduces to a linear relationship.

Therefore, this suggests that the wear behaviour of these polymers may be explained better based on the exponents obtained from the non-linear relationship between volume loss of polymers and different operating variables.

Since the slopes of the best fit straight line in the logarithmic coordinates were to be used in the non-linear model, the individual set of slopes of each set of tests were analyzed and conditioned statistically (A sample analysis is shown for delrin, in Appendix 3: Table A.3.2(e)). The mean slope of the straight lines were the exponents used in the non-linear model and are tabulated in Table 4.1.

It can be seen from the Table 4.1 that the exponents are different for each polymer as might be expected. For all the polymers tested the exponent 'p' with contact load is highly significant and is the highest, except for HDPE for which the exponent with speed is the highest. This suggests that load is the most critical operating

Table 4. 1: *Exponential parameters for different polymers against both counterfaces*

MATERIAL	p	q	r	s
Delrin	1.711	1.711	1.024	0.728
High Density Polyethylene	1.364	2.425	1.229	1.470
Poly Vinyl Chloride	2.041	1.152	0.679	0.949
Rulon	1.381	0.665	0.764	0.625
Teflon(m)	1.497	0.695	0.772	0.258
Teflon(v)	1.287	0.845	0.681	0.610

variable compared to other variables. The exponent 'q' with speed for delrin and PVC are also significant when compared to other polymers. The exponent 'r' with time for delrin and HDPE are higher than the exponents in the same range for other polymers. The exponents with all the operating variables for HDPE are comparatively higher than the exponents of all other polymers. The exponent's' with counterface roughness for teflon(m) is the lowest among all the exponents of the polymers which means that the wear of teflon(m) was less affected with the counterface roughness than noted with the other polymers. The exponents for delrin, HDPE, and PVC are approximately in the same range and the rest of the polymers rulon, teflon(m), and teflon(v) are in one range.

However, to reconfirm the rejection of a linear relationship, Equations 3.5a and 3.5b established in Chapter 3 were analyzed for uncertainty. The wear coefficients determined from both models were compared and a sensitivity analysis was carried. Equation 3.5a for the linear model is

$$V = \frac{k_w W v T \alpha}{\gamma} . \qquad 4.4$$

Except for the surface energy of the polymer, not all the material properties are included. Equation 4.4 has only the operating variables which are directly proportional and surface energy inversely proportional to the volume loss. Thus wear coefficient is simply a number representing the intricate relationship between the variables not found in the equation. But this was not intended, as the main objective in the development of the equation was to have all the variables included. Equation 4.4 is written in terms of the wear coefficient as

$$k_w = \frac{V\gamma}{WvT\alpha} . \qquad 4.5$$

The wear coefficient is only a function of volume loss, operating variables and the surface energy, which is a constant for the given material. Equation 4.5 reduces to

$$k_w^* = \frac{V}{WvT\alpha} . \qquad 4.5a$$

Except for the counterface roughness term, this is the equation developed by Lewis [112]. But this has been shown by other researchers to have limited application since it does not consider material properties which are known to influence wear.

With the non-linear representation, wear volume appeared to possess a unique relationship with each operating variable and hence with other material properties. Equation 3.5b from Chapter 3 for the non-linear relationship is

$$V = k_w W^p v^q T^r \alpha^s E^{(-3+p+r+s)} \gamma^{(3-2p-q-s)} (C_p/K)^{(r-q)} . \qquad 4.6$$

Equation 4.6 is written interms of the wear coefficient as

$$k_w = \frac{V}{W^p v^q T^r \alpha^s E^{(-3+p+r+s)} \gamma^{(3-2p-q-s)} \left(\frac{C_p}{K}\right)^{(r-q)}} . \qquad 4.7$$

Equation 4.7 incorporates all the variables believed to be significant in developing a wear equation. Hence, this should yield a better representation of the wear coefficient than obtained from the linear analysis. The following sections deal with uncertainty analysis of the models, the evaluation, sensitivity and comparison of the wear coefficients from both the linear and exponential relationships.

4. 4. 2. UNCERTAINTY OR ERROR ANALYSIS OF THE PROPOSED MODELS:

In order to evaluate the fractional uncertainity in the wear coefficients from the proposed models a general function 'U' is considered. Let 'U' be a function evaluated from variables a_1,----,a_n, b_1,----,b_n expressed as

$$U = \frac{a_1 \times \text{---------} \times a_n}{b_1 \times \text{---------} \times b_n} \ . \qquad 4.8$$

Suppose that variables a_1,----,a_n,b_1,----,b_n are measured with uncertainties δa_1,----, δa_n,δb_1,----,δb_n and if the uncertainties in these variables are independent and random, then the fractional uncertainty in 'U' is the sum in quadrature of the original uncertainties, and written as

$$\frac{\delta U}{|U|} = \sqrt{\left(\frac{\delta a_1}{a_1}\right)^2 + \text{----} + \left(\frac{\delta a_n}{a_n}\right)^2 + \left(\frac{\delta b_1}{b_1}\right)^2 + \text{----} + \left(\frac{\delta b_n}{b_n}\right)^2} \ . \qquad 4.9$$

The above principle [117] is applied to find the fractional uncertainty in the wear coefficients for both the linear model and the non-linear model. Equation 4.5 for the wear coefficient from the linear model is

$$k_w = \frac{V\gamma}{WvT\alpha} \ . \qquad 4.5$$

The fractional uncertainty equation for k_w from Equation 4.5 is written as

$$\frac{\delta k_w}{|k_w|} = \sqrt{\left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta \gamma}{\gamma}\right)^2 + \left(\frac{\delta W}{W}\right)^2 + \left(\frac{\delta v}{v}\right)^2 + \left(\frac{\delta T}{T}\right)^2 + \left(\frac{\delta \alpha}{\alpha}\right)^2} \ . \qquad 4.10$$

Equation 4.7 for the wear coefficient from the non-linear model is

$$k_w = \frac{V}{W^p v^q T^r \alpha^s E^{(-3+p+r+s)} \gamma^{(3-2p-q-s)} \left(\frac{C_p}{K}\right)^{(r-q)}} \ . \qquad 4.7$$

Uncertainty in a power is found as follows; if the quantity i_1 is measured with uncertainty δi_1 and the measured value used to compute the power $I = i^n$ (where n is a fixed, known number), then the fractional uncertainty in I is $|n|$ times that in i, expressed as

$$\frac{\delta I}{|I|} = |n| \frac{\delta i}{|i|} . \tag{4.11}$$

The fractional uncertainty equation for k_w from Equations 4.7 and 4.11 is written as

$$\frac{\delta k_w}{|k_w|} = \sqrt{\left(\frac{\delta V}{V}\right)^2 + \left(p\left(\frac{\delta W}{W}\right)\right)^2 + \left(q\left(\frac{\delta v}{v}\right)\right)^2 + \left(r\left(\frac{\delta T}{T}\right)\right)^2 + \left(s\left(\frac{\delta \alpha}{\alpha}\right)\right)^2 + \left((-3+p+r+s)\left(\frac{\delta E}{E}\right)\right)^2 + \left((3-2p-q-s)\left(\frac{\delta \gamma}{\gamma}\right)\right)^2 + \left((r-q)\left(\frac{\delta C_p}{C_p}\right)\right)^2 + \left((q-r)\left(\frac{\delta K}{K}\right)\right)^2} . \tag{4.12}$$

Fractional uncertainties in individual variables:

1. Wear volume: sensitivity of the electronic balance = ±0.0001 grams and the average weight of the polymer specimen = 0.7500 grams, therefore $\delta V/V = 1.33 \times 10^{-4}$.

2. Normal load: sensitivity of the balance = ±0.1 lbs, moment arm ratio = 2, weight measured = 10 lbs, therefore $\delta W/W = (0.1x2)/10 = 0.02$.

3. Sliding speed: sensitivity of tachometer = ±1 rpm, sensitivity of micrometer in measuring the diameter(d) of the disk = ±0.001 inches, n = 100 rpm, d = 3.75 inches, sliding speed = $\pi(2.54x10^{-3}d)n/60$, therefore $\delta v/v = (\delta n/n) + (\delta d/d) = 0.0103$.

4. Sliding duration: $\delta T/T = 0.03\% = 0.0003$ (corresponds to measuring time to ±5 sec accuracy and the minimum time measured was 18000 sec except for teflon).

5. Counterface roughness: sensitivity of talysurf instrument = ±0.2 micro-inches, minimum roughness measured = 2 micro-inches, therefore $\delta\alpha/\alpha = 0.2/2 = 0.10$.

6. Surface energy: surface energy was evaluated using a surface contact angle measurement, sensitivity of the contact angle measurement apparatus = ±1 degree, angle measured = 100 degrees, therefore $\delta\gamma/\gamma = 1/100 = 0.01$.

7. Modulus of elasticity: uncertainty of 1% was assumed as per standard practice, $\delta E/E = 0.01$.

8. Specific heat: uncertainty of 1% was assumed as per standard practice, $\delta C_p/C_p = 0.01$.

9. Thermal conductivity: uncertainty of 1% was assumed as per standard practice, $\delta K/K = 0.01$.

Now substituting the fractional uncertainties of individual variables in Equation 4.10 the fractional uncertainty in the wear coefficient from the linear model was calculated to be to 10%. It was seen that the fractional uncertainties in V, γ, v and T had a negligible effect on the wear coefficient. Hence, the fractional uncertainty in the wear coefficient was mainly affected by the uncertainties in load and the counterface roughness.

The fractional uncertainty in the wear coefficient for the non-linear model was calculated from substituting the fractional uncertainties of the individual variables in Equation 4.12. The determination of the wear coefficient was comparatively more complex since the non-linear model involved exponents. From the statistical analysis the percentage error for the mean exponent was found to be within ±3%. Therefore, the mean exponent was used for carrying out the uncertainty analysis. In this case, the fractional uncertainty in the wear coefficient was not only dependent on the fractional uncertainties of variables such as load, sliding speed, counterface roughness, etc., but also they were dependent on the exponents. The lowest fractional uncertainties in the wear coefficients for polymers were found in cases where the exponents were lower than unity. This was because the fractional uncertainty in individual variables was multiplied by the exponent. The lowest fractional uncertainty of 4% was found with teflon(m) and the highest was found for HDPE at 15%.

The above analysis predicted different uncertainties in the wear coefficients for different polymers due to the non-linear relation between volume loss and the operating variables, whereas the linear model showed a single uncertainty for all polymers. But this is unlikely to happen since the wear coefficient for different polymers is not the same and the wear coefficient is a unique function of different variables for a given polymer. The uncertainties in the wear coefficients from both models were largely due to the maximum uncertainty in counterface roughness. The non-linear model will predict a low uncertainty if the exponents are lower than unity where a linear relationship does not exist. Thus, the prediction of uncertainties in wear coefficients based on a non-linear relationship interprets the wear coefficient more appropriately than the linear model.

4. 4. 3. DETERMINATION OF THE WEAR COEFFICIENT:

After all the variables (material properties tabulated in Table A.3.1 and mean value of the wear results in Tables A.3.3-A.3.14) are known in the wear equation, the dimensionless wear coefficient k_w can be calculated. The final wear coefficient for the given material was found by statistical analysis and conditioning of wear coefficients obtained for each of the different variables as explained above. This was carried out for wear coefficients obtained from both linear and non-linear analysis (Appendix 3: Tables A.3.2(f) - A.3.2(g)). In case of some of the polymers tested, one or two data points were rejected for statistical conditioning of the data set. The dimensionless wear coefficients of all polymers are tabulated in Table 4.2. A wear equation can now be written for each polymer material as follows; for example, for delrin sliding against both steel counterfaces, the wear equation for the linear model is given by

$$V = 1.74 \times 10^{-10}\, W\, v\, T\, \alpha\, \gamma^{-1}\,, \tag{4.13a}$$

and for the exponential model is given by

$$V = 3.56 \times 10^{-18}\, W^{1.711}\, v^{1.711}\, T^{1.024}\, \alpha^{0.728}\, E^{0.463}\, \gamma^{-2.861}\, (C_p/K)^{-0.687}. \tag{4.13b}$$

Similarly, the wear equation for other materials HDPE, PVC, rulon, teflon(m) and teflon(v) sliding against steel counterfaces can be written.

4. 4. 4. SUMMARY OF THE WEAR COEFFICIENT EVALUATION:

Table 4.2. summarizes the dimensionless wear coefficients (mean and its ranges) evaluated for different polymers from both the linear and the non-linear models.

4. 4. 4(A). WEAR COEFFICIENTS FROM LINEAR MODEL:

It has been already discussed that by considering a linear relationship of volume loss with the operating variables there is no advantage in the development of a new wear equation to describe the wear of polymers since the model does not take into consideration all the material properties influencing the wear. The appropriateness of this wear equation remains doubtful. It can be seen from the above Table 4.2 the wear coefficients for all the polymers tested except teflon(m) and teflon(v) are approximately in the same range ($0.6\text{-}8\times10^{-10}$). This is because the linear wear equation uses the same values for all the terms except surface energy and the wear volume and the surface energy and the wear volume do not change much from one material to another. For both teflon(m) and teflon(v) the wear coefficients are in the same range for the same reasons. Therefore, these wear coefficients are unable to explain the effect of material properties which are known to influence the wear process and hence the wear coefficient. The main objective of developing a wear equation involving all pertinent material properties is not achieved by this simplification of the model. As well, from a statistical analysis and conditioning of the wear coefficients obtained from the linear model, it is seen that the percentage error in the wear coefficient is always higher than in the case for the non-linear model.

Table 4. 2. Average dimensionless wear coefficient of different polymers for the linear and the non-linear models

POLYMER	WEAR COEFFICIENT [k_w ± % Error] linear model	WEAR COEFFICIENT [k_w ± % Error] non-linear model
Poly Vinyl Chloride	2.08E-10 ± 4.4%	4.47E-19 ± 2.1%
Delrin	1.74E-10 ± 4.0%	3.59E-18 ± 2.3%
High Density Polyethylene	8.10E-10 ± 6.1%	1.12E-16 ± 3.8%
Rulon	6.26E-11 ± 4.3%	1.03E-11 ± 2.2%
Teflon(m)	1.07E-07 ± 6.3%	2.99E-09 ± 0.7%
Teflon(v)	9.91E-08 ± 4.5%	1.16E-05 ± 2.2%

Sensitivity analysis of the wear coefficients with each operating variable:

To study the sensitivity of these wear coefficients graphs were plotted with the operating variables (Figures A.3.13 - A.3.18). A large scatter in the wear coefficients from the mean value line was seen in the wear coefficients with each operating variable for most of the polymers tested. In some cases the wear coefficients seem to be influenced by the operating variables either by increase or decrease in the values. But this was not expected for the wear coefficient as it is assumed to be a proportionality constant for a given polymer.

4. 4. 4(B). WEAR COEFFICIENTS FROM NON-LINEAR MODEL:

It can be seen from Table 4.2 that the order of the dimensionless wear coefficients varies significantly for different polymers. This indicates the influence of the material properties on the wear coefficient of polymers which would not be seen in the case of the linear model. The magnitude of this wear coefficient can be used to predict the wear volume of a polymer sliding against a steel counterface. As can be seen from Table 4.2 teflon(v) had the highest wear coefficient and PVC had the lowest wear coefficient of all the polymers tested. It can also be seen from the wear results that teflon(v) had the highest wear volume and PVC had a comparatively low wear volume among the polymers tested. For both PVC and delrin the wear coefficients were approximately of the same order. One of the important material parameters responsible for the low wear coefficient of these polymers is their modulus of elasticity, which is the highest for both PVC and delrin when compared to other polymers tested. It is seen that all other material properties of the polymers considered in the wear equation differed by a marginal value. The same observation applies to HDPE with a higher modulus of elasticity than rulon. HDPE had a comparatively lower wear coefficient than rulon, which wore much less than HDPE. This leads to the observation that the wear coefficient can be used to represent the wear volume or wear potential of a particular polymer, suggesting that a universal wear constant or coefficient does not exist for all the polymers.

The lower wear volume of rulon with a wear coefficient higher than any of the above polymers can be explained as follows; rulon is a ceramic filled fluorocarbon belonging to the family of teflon which has a comparatively high wear coefficient. The material properties of rulon do not vary much compared with those of teflon whose modulus of elasticity and surface energy are lower than the other polymers considered. Rulon exhibits superior wear resistance compared with ordinary teflon due to its composition and structure but has a low coefficient of friction similar to teflon. As can be seen from Table 4.2 teflon(v) had the highest wear coefficient indicating a higher volume loss. According to the manufacturer, teflon(m) which has recycled teflon scrap in its composition, exhibits a comparatively better wear resistance due to cross linking of the teflon matrix. This was confirmed from experiments where the wear coefficient evaluated was lower than teflon(v). The wear behaviour of teflon(v), teflon(m) and rulon observed during the test, the friction and wear results obtained during sliding against both counterfaces, and the SEM photographs of the worn surfaces revealed that they have a unique wear behaviour independent of the counterface not seen with any other polymers. The wear coefficients of these polymers suggests they can be considered as a single category.

The wear coefficients evaluated can be grouped into two classes. Among the polymers tested, PVC, delrin and HDPE can be grouped within one class with their wear coefficient varying between three orders of magnitude. Teflon(m), teflon(v) and rulon (ceramic filled fluorocarbon) can be grouped under a separate class with the wear coefficients of teflon(m) and teflon(v) varying between four orders of magnitude and rulon, a filled fluorocarbon with two orders of magnitude lower than teflon(m) and teflon(v). This suggests that polymers having the same molecular structure may possess a common wear coefficient which is applicable under all conditions.

Statistical analysis and conditioning of the wear coefficient data evaluated for all operating variables showed that the percentage error in the mean value of the wear coefficient is less than that found in the linear model. It can be seen from Table 4.2 that the wear coefficient explicitly represents the wear behaviour and it does not hide the material properties as they are independently represented in the wear equation.

Therefore, the wear equation developed from the non-linear relationship is more appropriate as all the parameters considered during dimensional analysis are retained.

Sensitivity analysis of the wear coefficients with each operating variable:

A sensitivity analysis was carried out by plotting the wear coefficients against the operating variables (Figures A.3.19 - A.3.24). The plots showed less scatter in the wear coefficients from the average wear coefficient. Most of the points were clustered closer to the line of the average wear coefficient. Thus, the wear coefficient was not much influenced by the operating variables. This is a highly significant and desirable feature of the proposed model. The uncertainty analysis which predicted lower uncertainties than the linear model adds to the confirmation that non-linear model represents the wear equation and the wear behaviour better than the linear model.

4. 5. COMPARISON BETWEEN THE PROPOSED EQUATION AND KAR AND BAHADUR'S EQUATION FOR THE WEAR OF POLYMERS

The exponential form of the equation for the wear of polymers proposed in this research closely resembles the model equation for the wear of unfilled and filled polyoxymethylene proposed by Kar and Bahadur {K & B} [11]. Some of the major differences and similarities between these two equations are listed below. In the proposed wear equation, the wear coefficients for six different polymers sliding against two steel counterfaces are obtained by incorporating normal load and counterface roughness in the wear equation. Wear coefficients for the same polymers were also determined as a check using the equation developed by K & B, where contact pressure was considered instead of normal load (contact pressure was calculated from dividing the normal load by the average contact area of the specimen) and the counterface roughness was not considered. The wear coefficients obtained in both cases are given in Table 4.3.

It can be seen from Table 4.3 that the wear coefficients obtained from the proposed equation in Column 1 approximately represents the volume loss of polymers tested and are comparable with the volume loss (listed in Tables A.3.3 - A.3.14 for all the polymers given in Table 4.3) of each polymer. These wear coefficients represent the wear potential of polymers listed. It can be seen that a large order of magnitude difference in the wear coefficients determined from both cases exists for a given polymer. The magnitude of the wear coefficients obtained from K & B's equation are large and vary randomly. These are also not agreeable with the volume loss of the polymer as can be seen from Tables A.3.3 - A.3.14. Therefore, these can not be used as a proportionality parameter as they do not represent the wear potential. This can be explained in the following detail; as an example, at a load of 88.96N, 0.5 m/s speed the wear volume of PVC was 5.86×10^{-10} cu.m compared with 1.44×10^{-7} cu.m. for teflon(v). But from Table 4.3 the wear coefficient for PVC obtained from K & B's equation is higher than the wear coefficient for teflon(v) which contradicts the result obtained for volume loss of these polymers.

Table 4. 3. Comparison of the average dimensionless wear coefficients of different polymers obtained from the proposed wear equation and Kar and Bahadur's wear equation.

POLYMERS TESTED	Wear Coefficients From Proposed Equation	Wear Coefficients From K & B's Equation
Poly Vinyl Chloride	4.47E-19	5.15E+20
Delrin	3.59E-18	9.65E+14
High density polyethylene	1.12E-16	6.01E+11
Rulon	1.03E-11	1.3E+14
Teflon(m)	2.99E-09	5.59E+17
Teflon(v)	1.16E-05	9.03E+18

The wear coefficients obtained from the proposed equation do not have the inconsistency seen in those obtained from K & B's equation. This is due to considering counterface roughness and normal load in addition to more tests conducted against different counterfaces, which has not been done in the case of K & B's wear equation. The proposed wear equation confirms that the counterface material and its roughness are important factors to be considered. A comparison between the proposed wear equation and K & B's wear equation is made on the following basis.

(a) Differences between proposed and K & B's model:

Proposed equation	Kar and Bahadur's equation
1. Counterface roughness is considered and therefore there are four dependent dimensionless groups which are used to describe the volume loss.	1. Counterface roughness is not considered. This results in only three dimensionless groups.
2. Normal contact load is considered.	2. Contact pressure is considered.
3. The average wear coefficients could be grouped into two ranges for two different groups of polymers. The wear coefficients represented a proportionality parameter in the wear equation and agreeable with the volume loss.	3. The average wear coefficients were found to be random and can not be used as a proportionality parameter in the wear equation. The wear coefficients were not agreeable with the volume loss.
4. The model investigated the influence of two counterface materials. Six different polymers were tested under identical operating conditions and these wear results were used in the development of the wear equation. The wear equation is well established and is agreeable with the results.	4. The model did not involve the effect of counterface materials on the wear process. Only two similar polymers were used in the experiments for developing a single equation. The validity of the wear equation is limited to two materials evaluated.

(b) Similarities:

Both models established exponential relationship between the volume loss and the operating variables chosen.

5. RESULTS AND DISCUSSION

5. 1. ANALYSIS OF THE EFFECT OF DIFFERENT OPERATING VARIABLES FROM THE HORIZONTAL PIN-ON-DISK MACHINE

(i) LOAD:

The volume loss (wear volume) vs. load for all polymers sliding against AISI 1018 steel and HTSR 4140 steel counterfaces is shown in Figure 5.1 and Figure 5.2 respectively. With an increase in load from 71 to 142N, the wear volume was observed to increase during the test. The insets in Figures 5.1 and 5.2, show the volume loss of teflon(m) and teflon(v) both of which had the largest wear volume of all polymers tested.

The wear volume was approximately the same at similar loads with both counterfaces for all the polymers except teflon(v) and delrin, where for teflon(v) the wear volume was more with AISI 1018 than HTSR 4140 and for delrin it was vice versa. In the case of delrin, PVC and rulon the rate of increase in wear volume with an increase in load was less when compared with other polymers. The increase in wear volume was significantly higher at higher loads than at lower loads for HDPE, delrin and PVC. Among all the polymers tested, rulon had the lowest rate of increase in the wear volume when load was increased.

At the start of a test the friction was very high during running-in and increased continuously during this break-in period for all the wear tests conducted with polymers used in this study. Later, the c.o.f. decreased initially before the steady state period after running-in for 15-60 minutes.

The variation of average steady state c.o.f. with load is plotted in Figure 5.3 against AISI 1018 and Figure 5.4 against HTSR 4140. It was seen that the c.o.f. of polymers tested varied during the steady state period of the tests. But for some polymers it was stable and remained constant at later stages of sliding. This frictional behaviour of all polymers was the same against both counterfaces but the average values of c.o.f. with different counterfaces were different for some polymers. The average c.o.f. for both teflon(m) and teflon(v) was lower than the c.o.f. for other polymers. The rate of

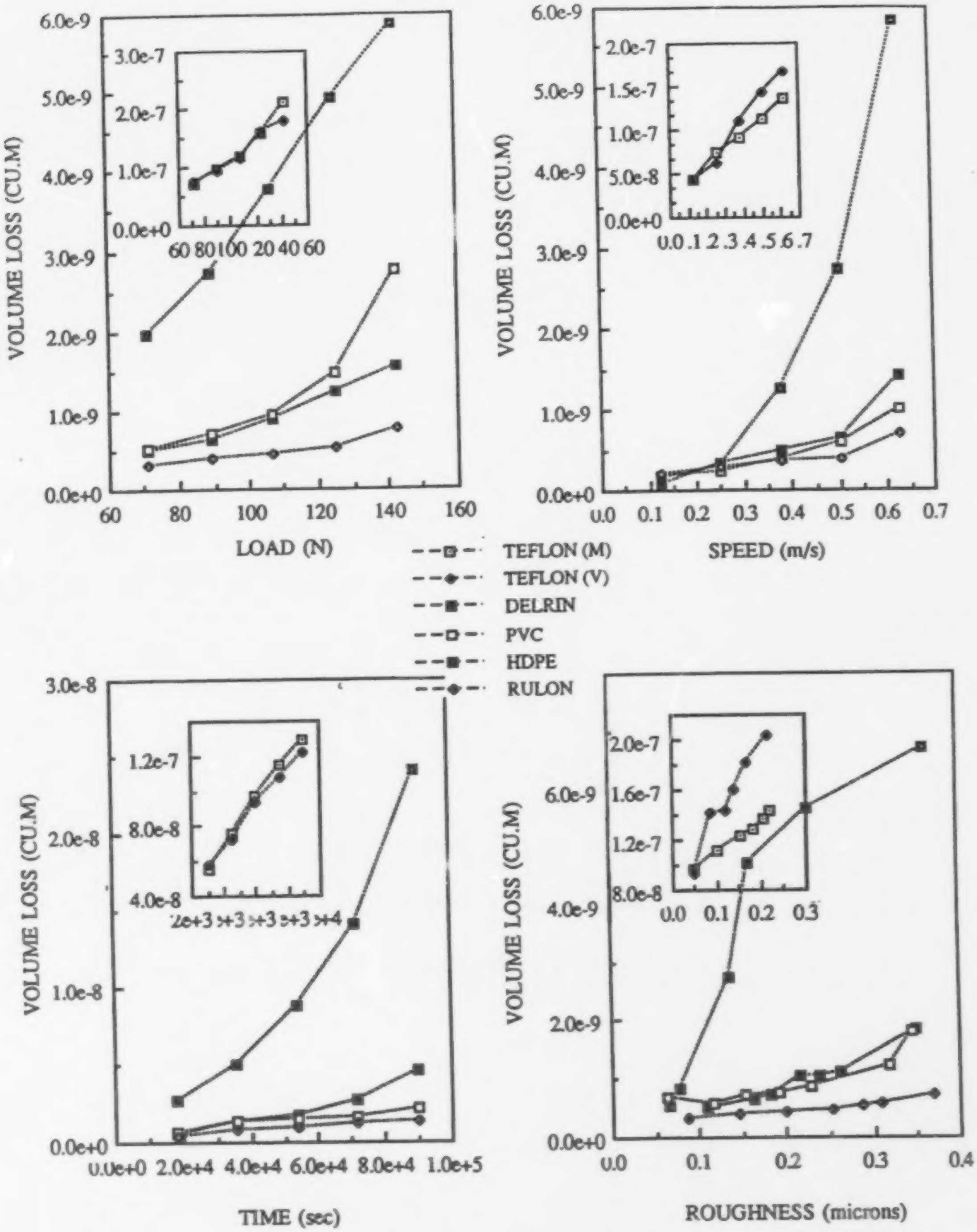


Fig. 5.1: Volume loss vs. different operating variables for different polymers sliding against AISI 1018 steel

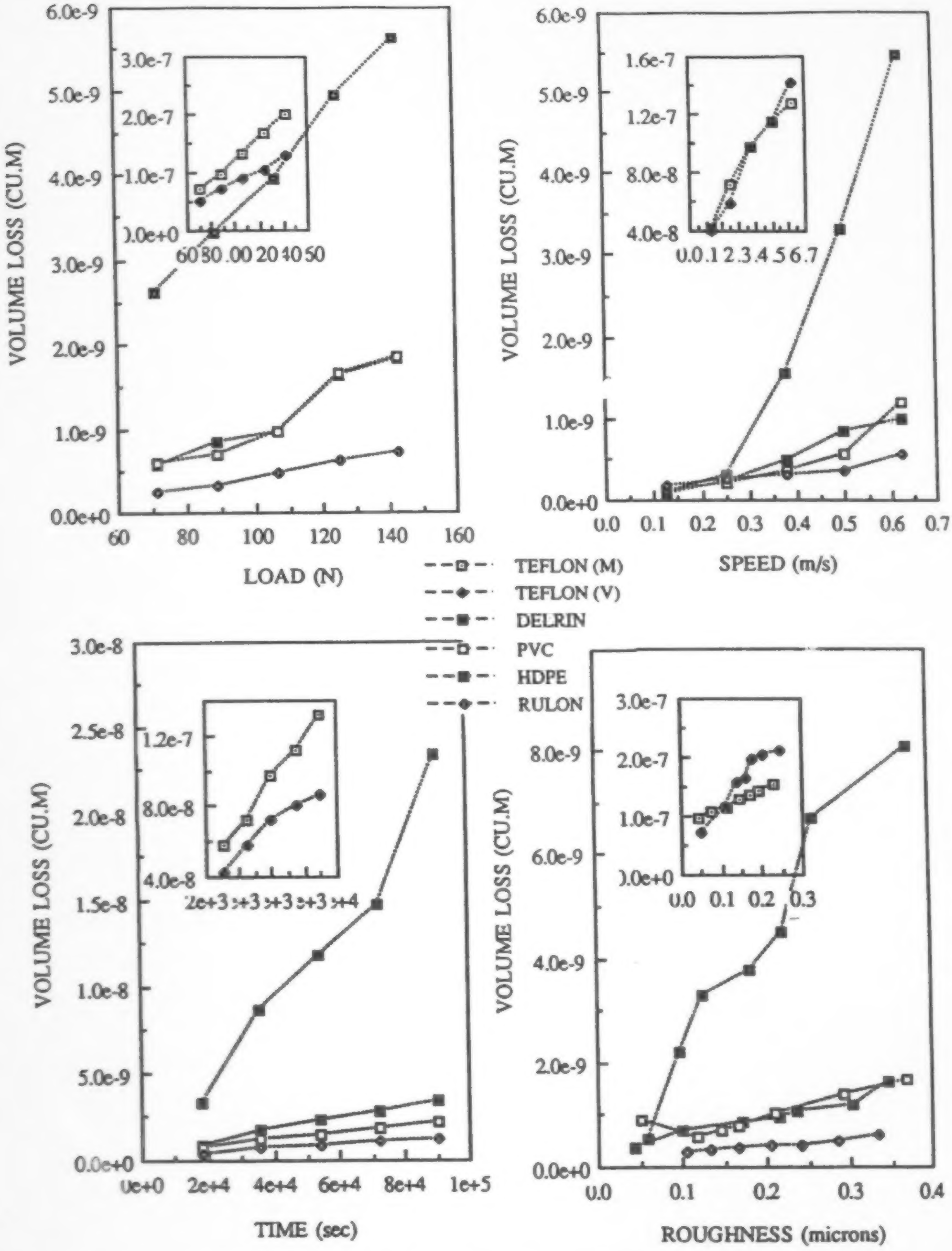


Fig. 5.2: Volume loss vs. different operating variables for different polymers sliding against HTSR 4140 steel

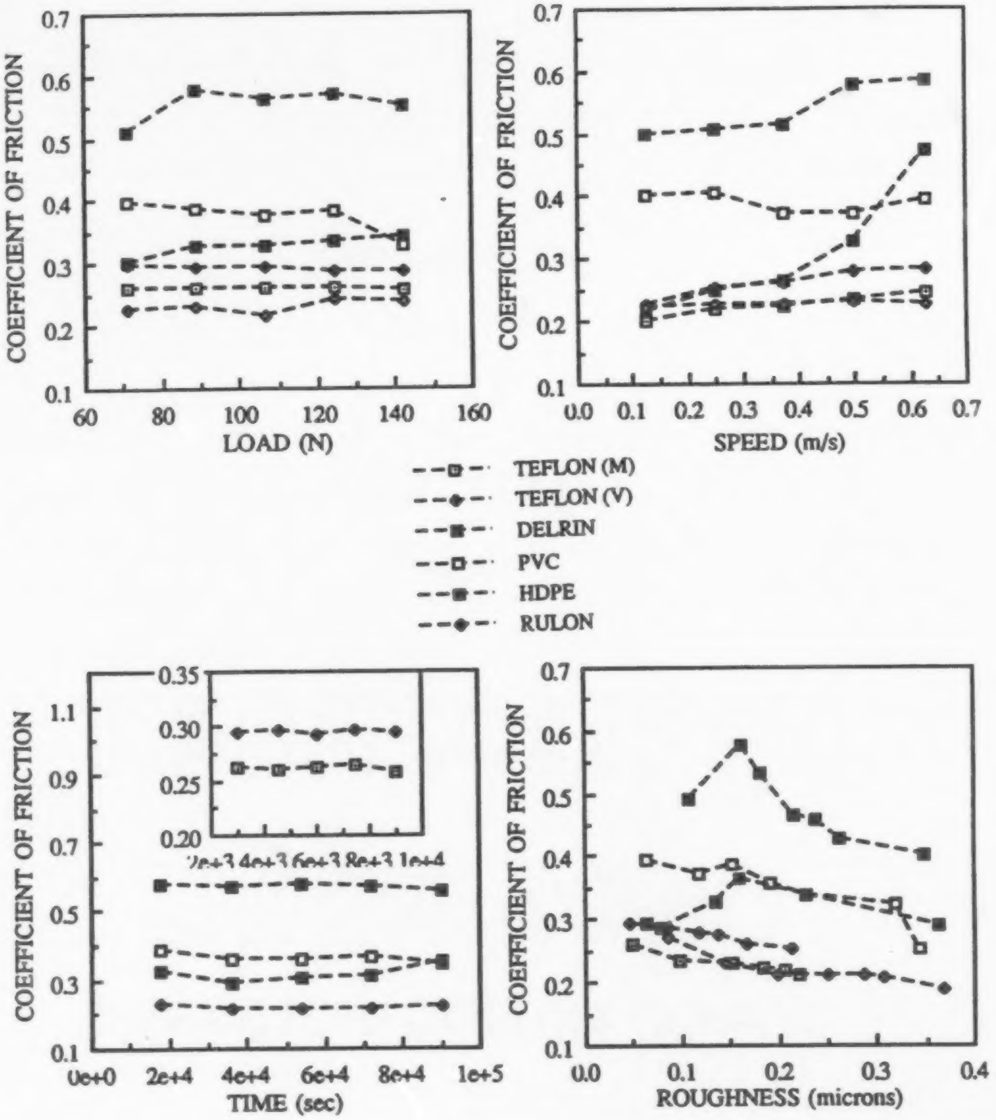


Fig. 5.3: Coefficient of friction vs. different operating variables for different polymers sliding against AISI 1018 steel

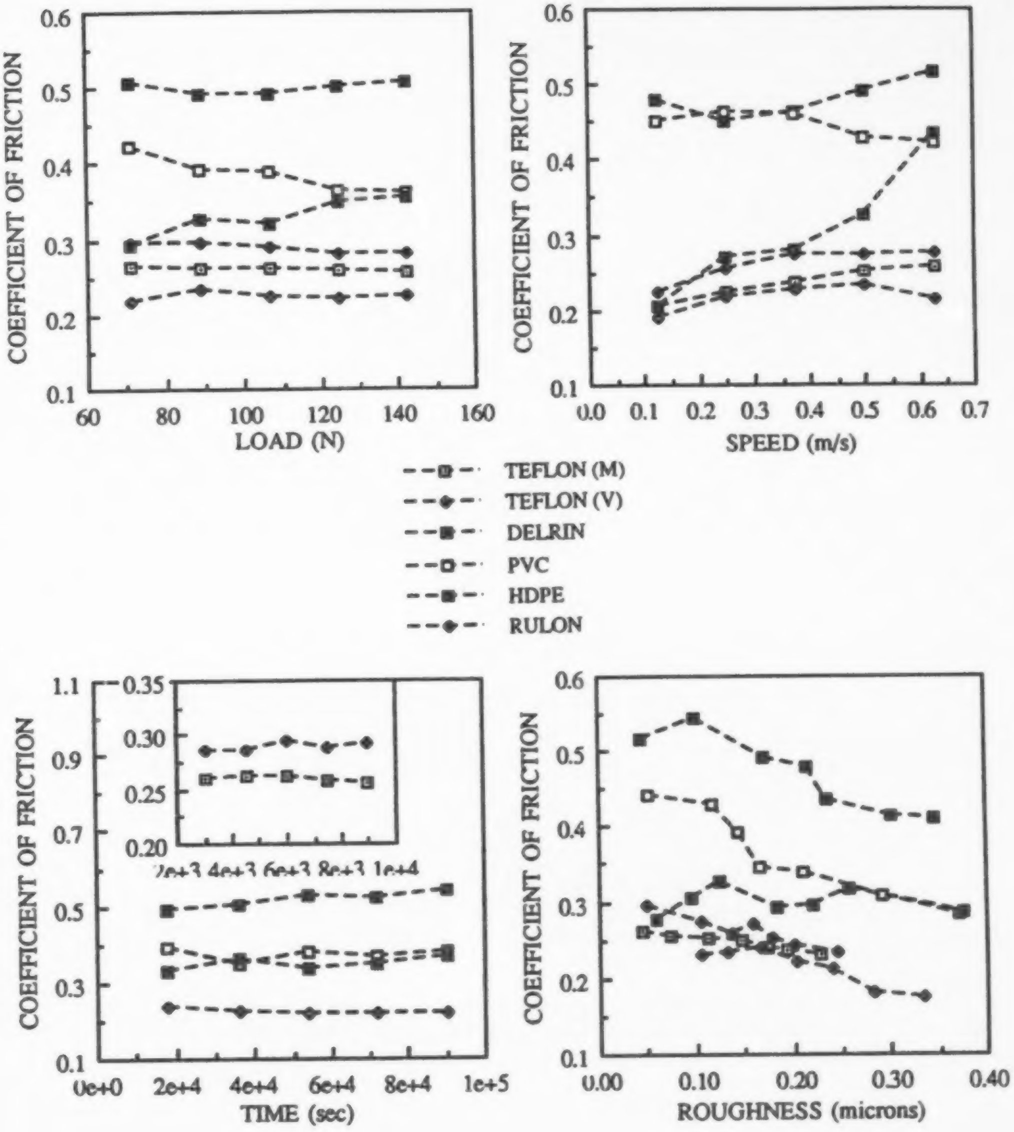


Fig. 5.4: Coefficient of friction vs. different operating variables for different polymers sliding against HTSR 4140 steel

increase in the c.o.f. for delrin and HDPE was larger in the initial stages of sliding where it increased almost two fold, but during the later stages of sliding the rate of increase dropped and the values increased constantly. A typical "stick-slip" behaviour of the frictional force was seen throughout the test for PVC sliding against both counterfaces and, after a peak value, the friction was found to decrease continuously. The wear debris from PVC while sliding was in the form of a fine powder which formed a thin coating on the counterface. This thin coating was scraped which resulted in the formation of a lump at the contact junction of the polymer and the counterface during sliding. The stick-slip phenomena occurred when this lump fell off as debris. An exception was that, the c.o.f. decreased slightly with an increase in load for PVC and it was vice versa for rulon. The reduction in the c.o.f. for PVC at higher loads might have been due to severe wear seen because of an increase in temperatures at the junction and plastic flow of the PVC surface.

(ii) SPEED:

The wear volume of polymers with sliding speed in the range 0.125-0.625 m/s is shown in Figures 5.1 and 5.2 AISI 1018 and HTSR 4140 counterfaces. From the wear results it is seen that wear volume of all polymers increased sharply with speed. The rate of increase in wear volume with increase in speed was considerably higher at higher speeds. The wear volume of teflon(m), HDPE and PVC was approximately the same against both counterfaces at the same sliding speeds, but the wear volume of teflon(v), delrin and rulon were higher against AISI 1018 than HTSR 4140. In the case of rulon, the rate of increase in wear with an increase in speed was found to be the lowest of all the polymers tested, though the wear volume at a lower speed was higher than the wear volume found at the same speed with some other polymers.

It was seen that with an increase in sliding speed, except for PVC, the c.o.f. increased for all polymers and was the largest at the highest speed (except for rulon). The variation of average steady state c.o.f. with sliding speed against both counterfaces is shown in Figures 5.3 and 5.4. The c.o.f. of all polymers except HDPE and rulon varied during the steady state period of the tests and the variation was severe at higher speeds. A high c.o.f. obtained during sliding at higher speeds may be attributed to high temperatures developed at the contact junctions. The c.o.f. for PVC was higher at a lower speed than the average c.o.f. at a higher speed. A variation was seen in the frictional behaviour of PVC and rulon with both counterfaces during all the tests. The average values of c.o.f. were different with different counterfaces under the same speed conditions for all polymers except for teflon(v) which was approximately in the same range.

(iii) DURATION OF TEST:

The variation of volume loss of all polymers with test duration against both counterfaces is shown in Figures 5.1 and 5.2. With an increase in duration of test (i.e., sliding distance) the wear of all polymers increased and the rate of increase was significant in the case of some polymers. It was observed that, usually, considerable wear occurred in the initial stages and, later as sliding time progressed, the wear stabilized reducing the rate of wear. This was because when a thin film of polymer formed on the counterface it modified the topography and changed the polymer-metal sliding to a polymer-polymer sliding situation. The wear volume of teflon(m) and PVC were approximately the same with both counterfaces for the same test durations and in case of teflon(v), the wear volume was higher against AISI 1018 than against HTSR 4140 counterface. But with all other polymers tested, the wear volume was not the same with different counterfaces, and it varied for different test durations.

The variation of c.o.f. with test duration for polymers against both counterfaces is shown in Figures 5.3 and 5.4. The average c.o.f. of all polymers except delrin and HDPE was approximately in the same range. The average c.o.f. for delrin increased against HTSR 4140 with an increase in sliding duration, but remained approximately the same with slight variations for AISI 1018. In the case of HDPE, an unconventional behaviour in the c.o.f. was observed with average values of c.o.f. varying with test durations. The values were mostly higher against HTSR 4140 than AISI 1018. In the case of rulon against both counterfaces, some variations in the c.o.f. at some particular test durations were observed. The c.o.f. increased continuously for all the polymers during the initial period of running-in as expected. The c.o.f. varied during the steady state period of the tests for all polymers, but for some, the c.o.f. stabilized and remained constant in the later parts of the test. The variation in the c.o.f. for PVC with time was due to averaging the stick-slip behaviour of friction during the test. These average values of c.o.f. were found to be constant during the steady state period of tests at all durations with both counterfaces.

(iv) COUNTERFACE ROUGHNESS:

The variation of volume loss of all polymers sliding against both counterfaces with roughness is shown in Figures 5.1 and 5.2. An increase in the counterface roughness increased the wear of all polymers. An exception to this was in the case of PVC and rulon where a contrasting behaviour was observed initially at a very low roughness of 0.05 micron. The wear volume was higher at this initial low roughness and was found to decrease when the counterface roughness was slightly increased. This was due to strong adhesion that occurred during sliding at low roughness of 0.05 microns and as the roughness was slightly increased the polymer film formed inhibited the wear which resulted in lower wear. But as the counterface roughness was further increased there was an increase in the wear volume due to abrasion.

At lower roughnesses, an increase in the wear volume of teflon(m), teflon(v) and HDPE was less significant than when compared to the wear volume at higher roughnesses. Significant increases in the volume loss were not found for delrin, PVC and rulon with an increase in the counterface roughness. Even at a very high roughness, the wear volume was no greater than when compared to the wear volume at lower roughnesses. This was due to the formation of thin film of polymer on the counterface in the early stages which reduced the rate of wear. The wear volumes of most of the polymers tested with both counterfaces were different at the same roughness, with few exceptions for some polymers at a particular roughness. However, counterface roughness appeared to be a critical factor for HDPE causing severe damage. Lower roughnesses produced low wear volumes, but as the roughness was increased, the wear volume increased significantly with both counterfaces. For HDPE, for example, an increase in the counterface roughness of six times increased the wear volume by 15 times. This was due to the nature of HDPE which was soft and hence highly susceptible to abrasion. However, the rate of increase of about two times in the wear volume of rulon (a ceramic filled fluorocarbon) with an increase in the counterface roughness by five times was small when compared to other polymers tested.

The variation in c.o.f. with counterface roughness is shown in Figures 5.3 and 5.4. The c.o.f. decreased with an increase in counterface roughness in most cases due to the formation of the polymer film responsible for lower friction. As already explained in previous cases, the c.o.f. of all polymers varied slightly during the steady state period of the tests and for some polymers it decreased at higher counterface roughnesses. The average c.o.f. against both counterfaces at the same roughness was in the same range for all polymers except for teflon(m), PVC and HDPE; teflon(m) and PVC were higher against HTSR 4140; HDPE was higher against AISI 1018. At a very high counterface roughness, a comparatively low c.o.f. for rulon was seen for both counterfaces in the tests conducted here.

An unusual behaviour in the c.o.f. was seen as the roughness was varied in the case of HDPE and delrin. Lower roughness of the counterface produced a lower c.o.f. An increase in counterface roughness up to a certain value increased the average c.o.f. This was not the normal behaviour expected or seen for any of the polymers. Later, the average c.o.f. decreased with an increase in counterface roughness as expected. The exact reasons for this behaviour are unknown but the preparation of the counterface for the test may have influenced this behaviour.

5. 1. 1. COMPARISON OF THE WEAR AND FRICTION BEHAVIOUR WITH AISI 1018 AND HTSR 4140 COUNTERFACES:

Figure 5.5 shows the comparison of the wear volume and c.o.f. for different polymers sliding against AISI 1018 and HTSR 4140 counterfaces at various sliding speeds {0.125 m/s, 0.25 m/s, and 0.5 m/s} and the results are tabulated in Appendix 3-Table A.3.15. From Figure 5.5 it can be seen that the wear volume and the c.o.f. for most of the polymers is dependent on the counterface.

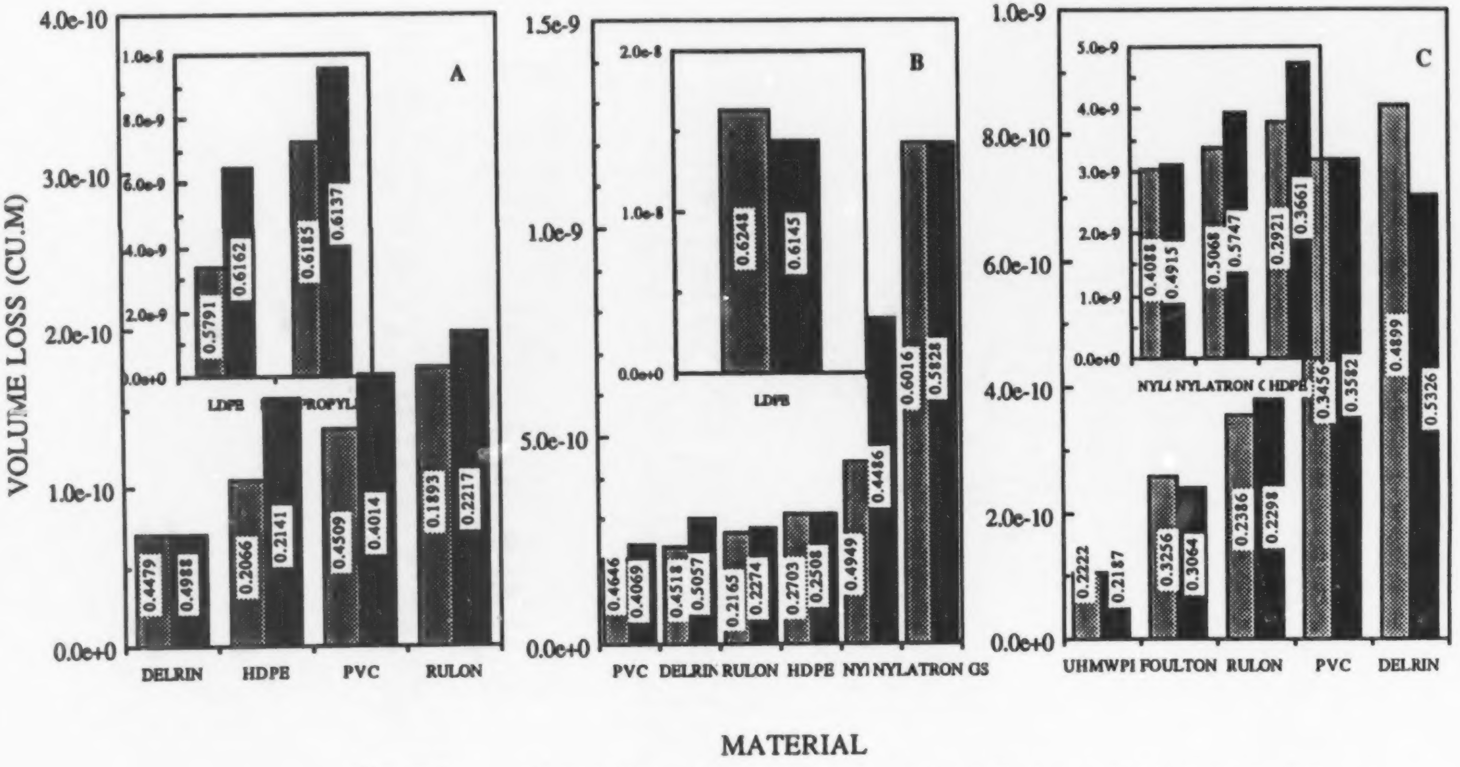


Fig. 5.5: Comparison of wear volume and coefficient of friction of different polymers sliding against AISI 1018 steel and HTSR 4140 steel counterfaces at various sliding speeds
{A}: 0.125 m/s; {B}: 0.25 m/s; {C}: 0.50 m/s;

At 0.125 m/s {A} all the materials, except delrin, had lower wear volume against HTSR 4140 than against AISI 1018 and the c.o.f. was different for most of the polymers with each counterface. At 0.25 m/s {B} only a few polymers had approximately the same wear volume when sliding against both counterfaces and the c.o.f. was different as in the previous case against both counterfaces. Similar wear and friction results were seen for most of the polymers tested at 0.5 m/s {C}.

From Figure 5.5 it is seen that the wear and friction of polymers tested was observed to change at varying speeds for both counterfaces under the same conditions of load, test duration and counterface roughness. It was observed that for some of the polymers tested, the counterface had a greater effect on the wear volume and c.o.f., whereas with other materials the effect was not as significant.

Figure 5.6 (results tabulated in Appendix 3-Table A.3.16.), represents a general comparison of the typical wear and friction normally observed in polymers sliding against AISI 1018 and HTSR 4140 counterfaces. The wear and friction behaviour was found to vary for each polymer under specific operating conditions with different counterfaces. These variations which might be limited to only a few of these polymers, have been pointed out to emphasise the fact that the material of the counterface influenced the wear and friction of polymers.

Figure 5.6 {A} shows the volume loss and c.o.f. of nylon for varying loads in the range of 36 - 90N. It can be seen that the wear volume and the c.o.f. are lower against HTSR 4140 than AISI 1018. It is also observed that the difference in the wear volume decreased with an increase in load. The c.o.f. values differed with each counterface.

Figure 5.6 {B} shows the volume loss and c.o.f. of teflon(v) where at all speeds the wear volume was lower against HTSR 4140 than against AISI 1018. The differences in wear volume increased with an increase in sliding speed in the range 0.125 to 0.625 m/s. The c.o.f. values were in the same range for both counterfaces at the same speeds.

Figure 5.6 {C} shows the volume loss of HDPE at varying test durations where the volume loss is lower against AISI 1018 than HTSR 4140 at all durations except at 25 hours where the volume loss is slightly higher. Some significant differences in wear

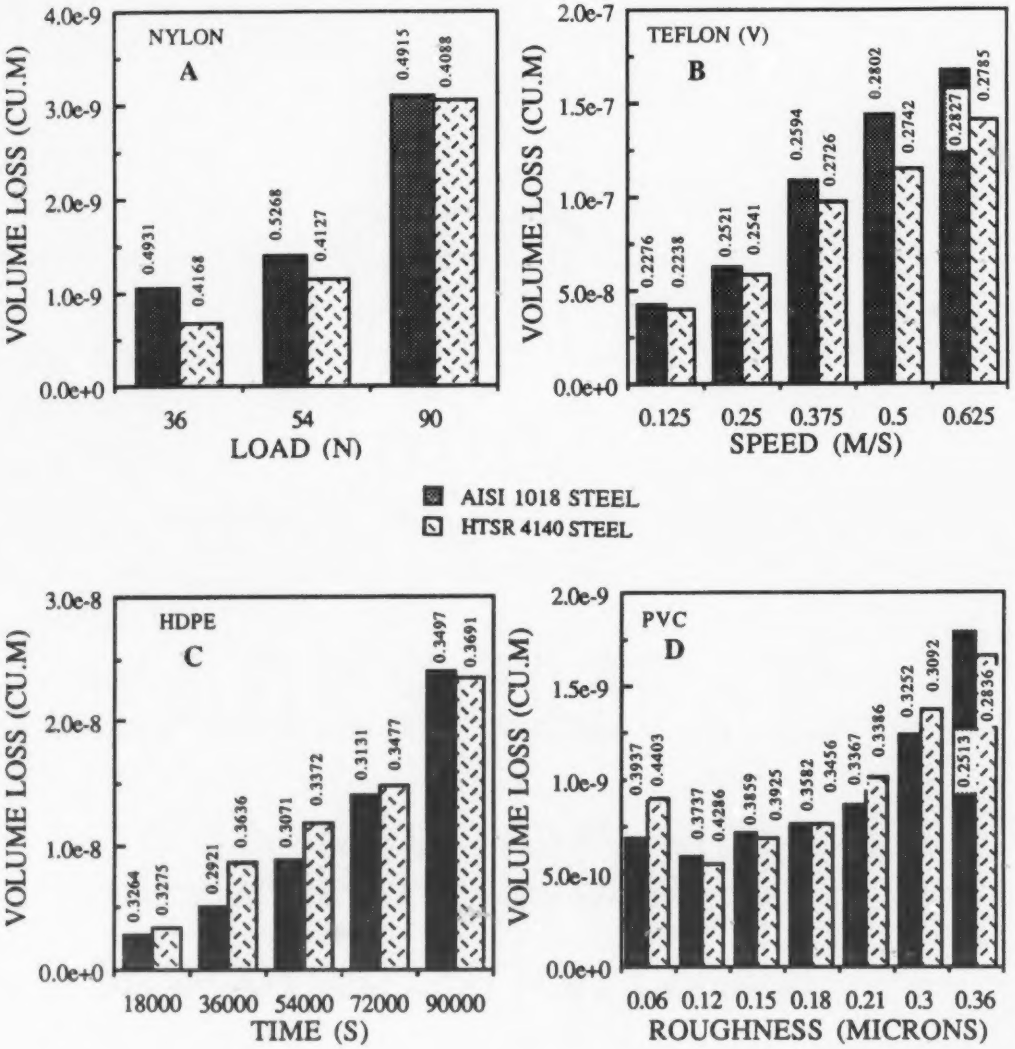


Fig. 5.6: General comparison of wear volume and coefficient of friction of different polymers sliding against AISI 1018 steel and HTSR 4140 steel counterfaces at different operating variables

volume are seen when the duration is 10 hours and 15 hours. The c.o.f. varies over a small range of values against both counterfaces.

Figure 5.6 {D} shows volume loss of PVC at varying counterface roughnesses where a small difference in the wear volume against both counterfaces at the same roughness was seen. Mostly at all roughnesses, the c.o.f. against AISI 1018 was found to be lower than the c.o.f. against HTSR 4140.

One material for each operating variable was considered to show that similar behaviours can be seen with all the polymer materials at other operating variables. It was also observed that the wear volume for the same polymer differed with each counterface under similar operating conditions. Only numerical data changed with other materials at different operating variables. The results shown in Figures 5.5 and 5.6 indicate the effect of counterface material on the wear and friction process of polymers.

5. 2. ANALYSIS OF THE EFFECT OF DIFFERENT OPERATING VARIABLES FROM THE VERTICAL PIN-ON-DISK MACHINE

From the data recorded (shown in Appendix 3: Tables A.3.17 - A.3.24) at different operating conditions during sliding of polymers on AISI 1018 and HTSR 4140 counterfaces on the vertical pin-on-disk machine, various graphs are plotted to compare the friction and wear of different polymers and are discussed below.

(i) SLIDING RADIUS / SPEED IN REVOLUTIONS PER MINUTE (RPM):

The graphs plotted in Figures 5.7 - 5.10, show the effect of speed (rpm) at two different counterface roughness (0.13 and 0.26 microns) on the wear and friction of several polymers. These tests were carried out for each counterface roughness keeping the other operating parameters constant. The surface sliding speed was chosen to be constant for all the tests at 0.5 m/s. The was done by changing the sliding radius and rpm of the disk which resulted in a different number of traverses on the wear track for each sliding radius on the disk during the test. This enabled to evaluate the effect of sliding radius during the tests.

Each figure has three graph blocks A, B and C because of large variations in the wear volume which could not be accommodated to the same scale for all the polymers. Block D in each figure shows the variation of c.o.f. with the rpm of the disk.

Figure 5.7 shows the variation of the wear volume and c.o.f. with rpm of the disk against an AISI 1018 counterface at a roughness of 0.13 micron. Except for delrin, the wear volume for all materials remained approximately the same and the c.o.f. was the same for all materials with an increase in rpm of the disk.

Figure 5.8 shows the above variation at a higher roughness of 0.26 micron for the AISI 1018 counterface. Wear volume did not change with changes in rpm or radius of the disk except with HDPE where there were fluctuations in wear volume. For polycarbonate, polypropylene and LDPE the wear volume increased with an increase in rpm. Whereas, for teflon(v) the wear volume decreased initially and then remained the same with an increase in rpm. The c.o.f. of polycarbonate, polypropylene and LDPE varied as the rpm and/or radius of the disk was varied, for the same surface speed.

By comparing Figures 5.7 and 5.8 for AISI 1018 at different counterface roughnesses, it can be seen that the wear volume of all polymers approximately remained the same, except for PVC and LDPE where the wear volume increased with an increase in roughness. The c.o.f. decreased for all polymers with an increase in roughness.

From Figure 5.9 for HTSR 4140 at a roughness of 0.13 micron it is shown that changes in the disk radius or rpm, keeping the surface speed constant, had no significant effect on the wear volume for most of the polymers tested. However, in the case of delrin, the wear volume increased continuously whereas it decreased for nylatron GS. For some of the other materials like polypropylene, teflon(m), and LDPE, the wear volume fluctuated with disk rpm. The c.o.f. did not change with disk rpm for most of the polymers, except for polypropylene and polycarbonate, where there was a slightly random behaviour in the friction values.

As shown in Figure 5.10 at a higher counterface roughness of 0.26 micron, changes in disk radius or rpm had no effect on the wear of most of the polymers, except that the wear of LDPE and polycarbonate increased steadily with an increase in disk rpm, and the wear of teflon(v) increased slightly at low speed and later decreased with an

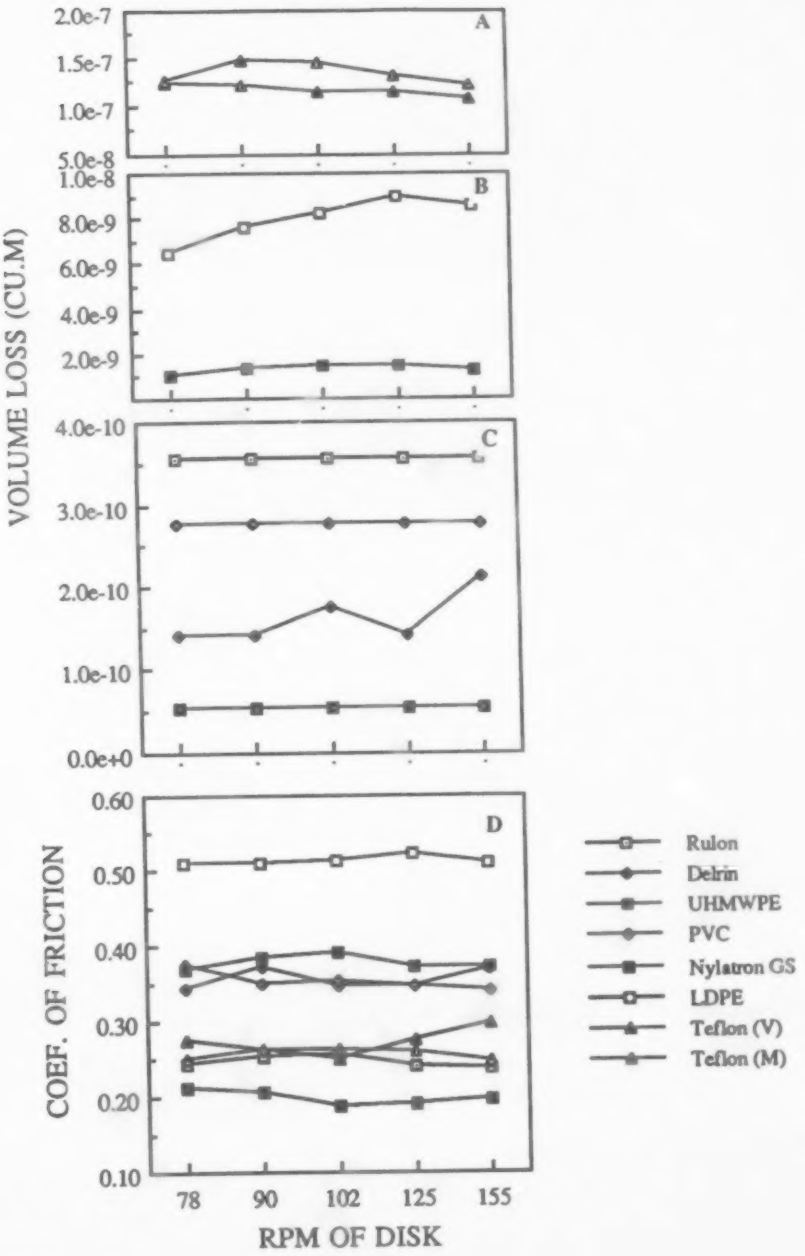


Fig. 5.7: Wear volume and Coefficient of friction of different polymers with disk rpm against AISI 1018 steel at counterface roughness of 0.13 microns load = 90N, surface speed constant at 0.5 m/s, duration = 5 hours

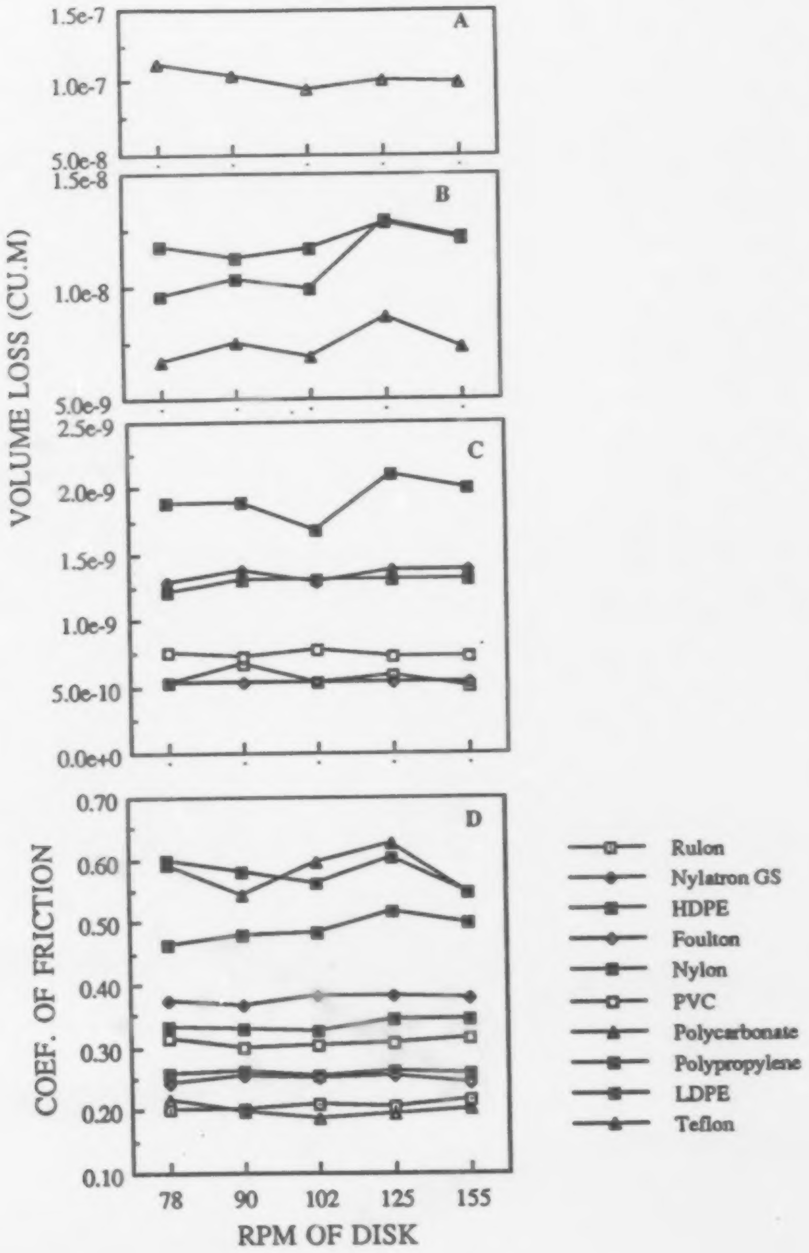


Fig. 5.8: Wear volume and Coefficient of friction of different polymers with disk rpm against AISI 1018 steel at counterface roughness of 0.26 microns load = 90N, surface speed constant at 0.5 m/s, duration = 5 hours

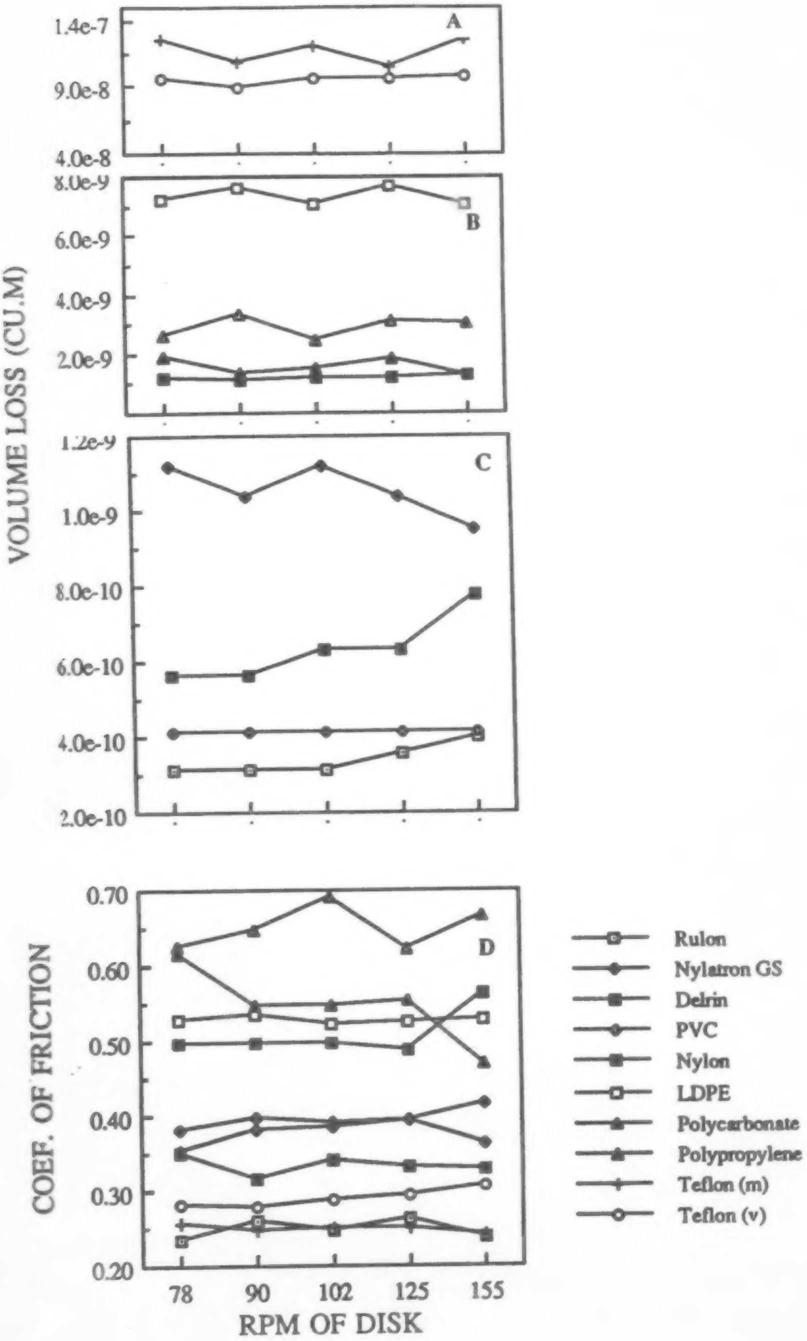


Fig. 5.9: Wear volume and Coefficient of friction of different polymers with disk rpm against HTSR 4140 steel at counterface roughness of 0.13 microns load = 90N, surface speed constant at 0.5 m/s, duration = 5 hours

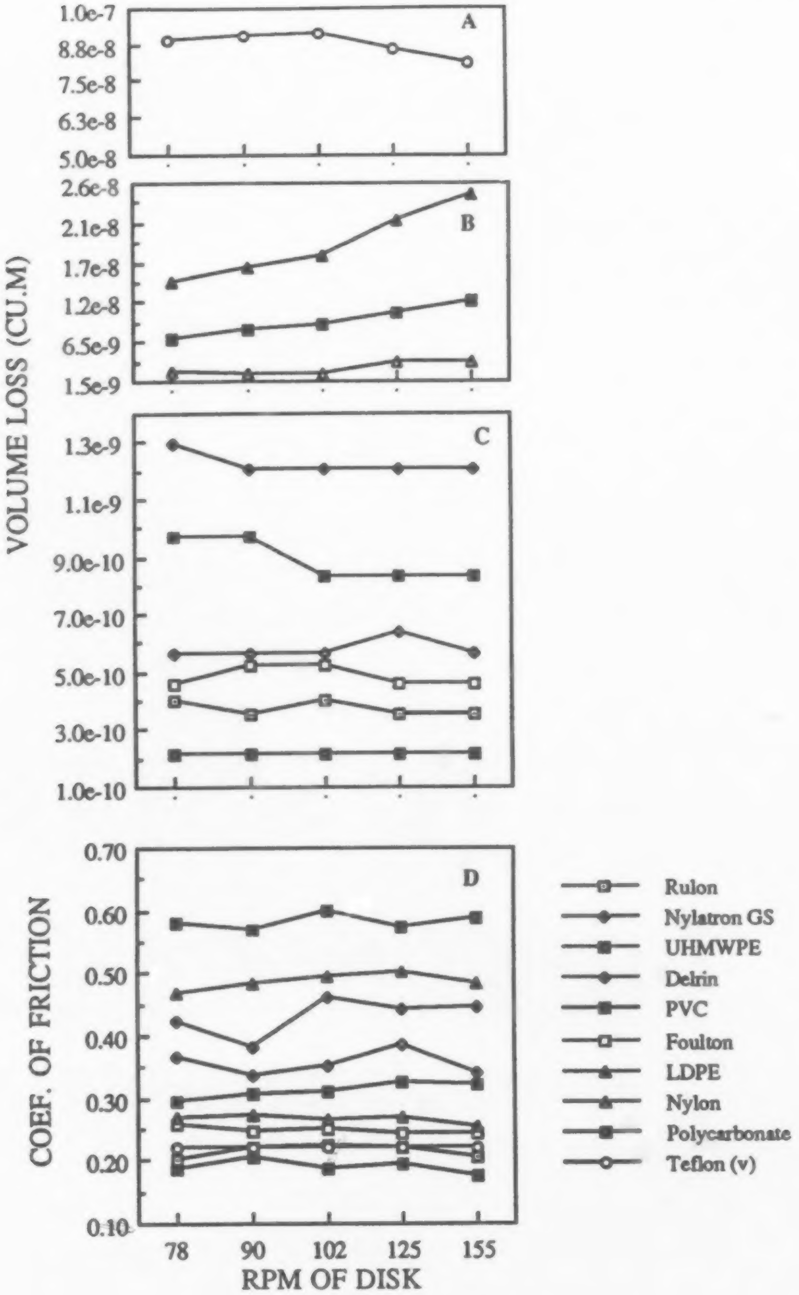


Fig. 5.10: Wear volume and Coefficient of friction of different polymers with disk rpm against HTSR 4140 steel at counterface roughness of 0.26 microns load = 90N, surface speed constant at 0.5 m/s, duration = 5 hours

increase in rpm. The c.o.f. remained the same with changes in disk radius or rpm for all polymers except for PVC, nylatron GS and delrin where there were fluctuations and in the case of LDPE, the friction increased with an increase in rpm.

Comparing the wear and friction of polymers tested from Figures 5.9 and 5.10 it is found that changes in the counterface roughness while not changing other parameters had some effect on the wear and friction behaviour, and for most polymer materials, the wear volume increased slightly with an increase in counterface roughness. A significant increase in wear volume was seen in some polymers such as polycarbonate, LDPE and nylon. The c.o.f. decreased slightly for all the polymer materials as a result of an increase in the counterface roughness.

(ii) SURFACE SLIDING SPEED:

Figures 5.11 and 5.12 show the wear and friction of different polymers tested at surface speeds of 0.125, 0.25 and 0.5 m/s against AISI 1018 and HTSR 4140 counterfaces at a roughness of 0.26 micron {A} and 0.13 micron {B}. In all cases, the wear increased with an increase in speed as expected and there was an increase in wear with an increase in speed from 0.25 to 0.375 m/s against AISI 1018 which was not found for HTSR 4140 counterface. In Figures 5.11 and 5.12 polycarbonate and teflon(v) are shown in the inset because they had higher wear volumes than the other materials. The c.o.f. was observed to vary randomly as speed was varied.

It can be seen from Figure 5.11 {A} nylon and HDPE had higher wear at 0.5 m/s than at lower speeds when compared to other materials. The c.o.f. of all polymers except rulon and LDPE varied with an increase in speed and the variations were more pronounced at higher speeds. At a lower roughness of 0.13 micron in Figure 5.11 {B} all polymers showed very little increase in wear volume with an increase in speed, except nylatron GS and LDPE which had a significant increase in wear volume with an increase in speed. The variation in the values of the friction of all polymers with an increase in speed was similar to that found at 0.26 micron. The average c.o.f. for some polymers was higher at 0.13 micron than the c.o.f. at 0.26 micron.

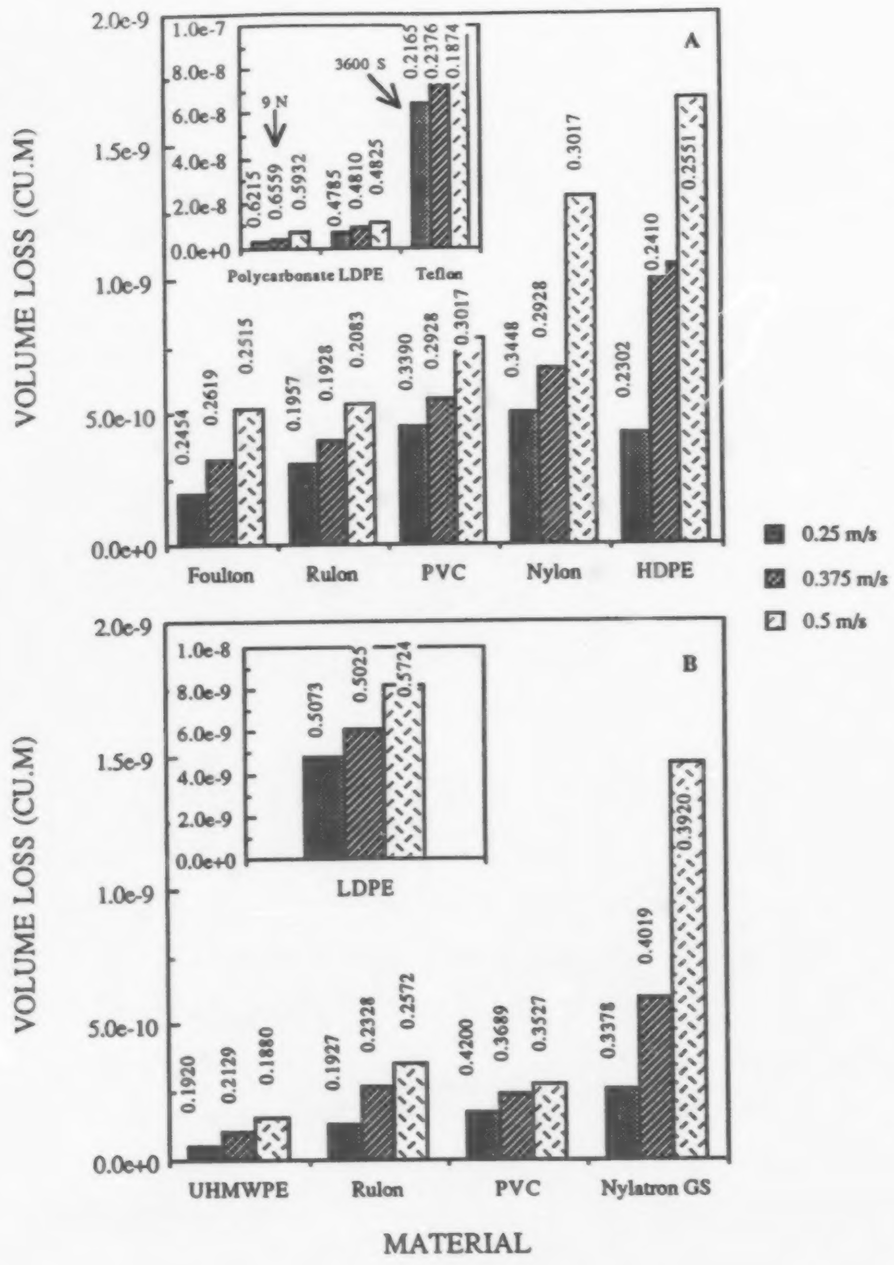


Fig. 5.11: Wear volume and Coefficient of friction of different polymers with sliding speed against AISI 1018 steel at different counterface roughnesses {A}: 0.13 microns; {B}: 0.26 microns; load = 90N, duration = 5 hours

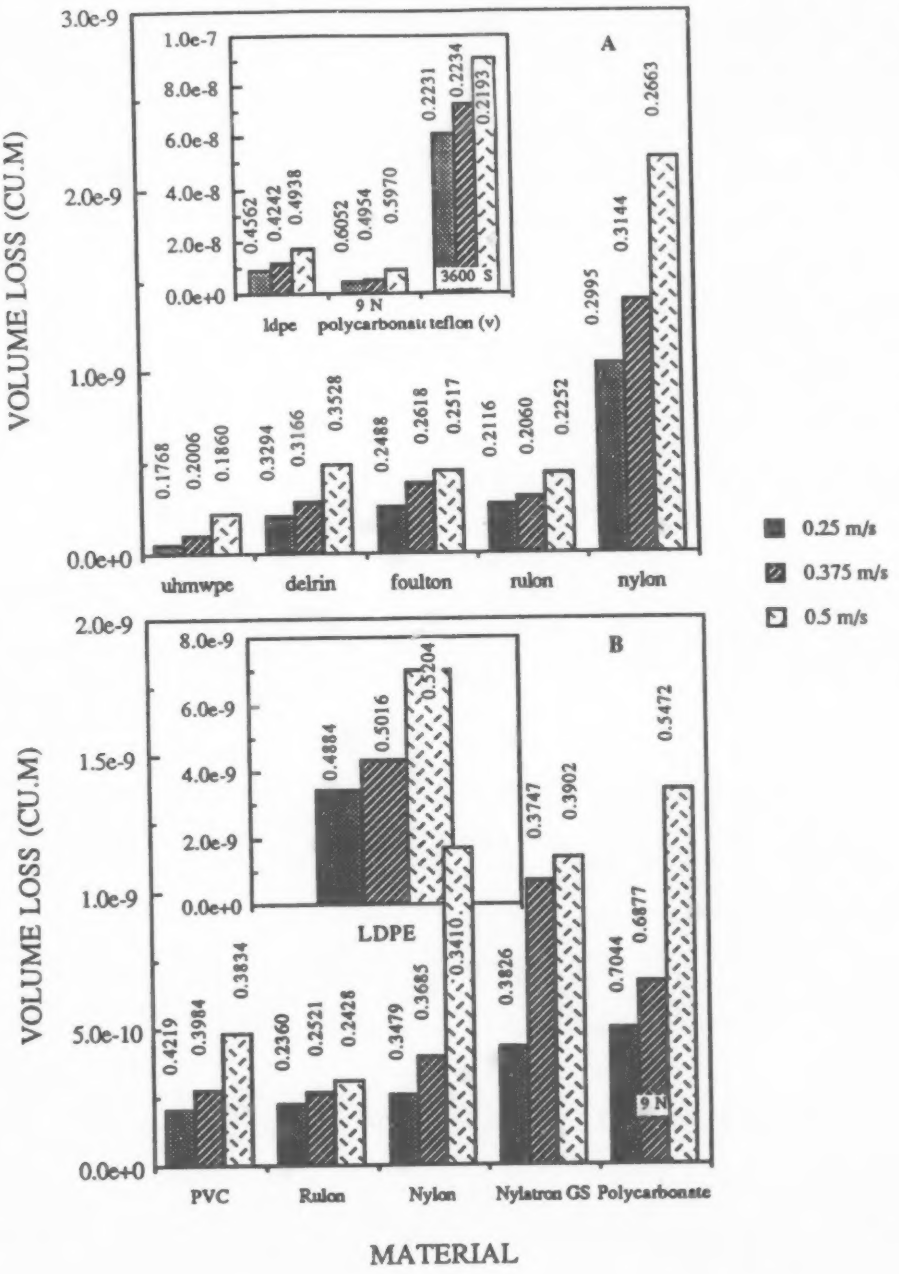


Fig. 5.12: Wear volume and Coefficient of friction of different polymers with sliding speed against HTSR 4140 steel at different counterface roughnesses {A}: 0.26 microns; {B}: 0.13 microns; load = 90N, duration = 5 hours

Figure 5.12 {A} shows that with HTSR 4140 counterface at a roughness of 0.26 micron, the wear and friction of polymers tested was similar to that observed in Figure 5.11 {A}. For some of the polymers the c.o.f. was higher at lower speeds, then decreased at intermediate speed and further increased with an increase in speed as expected. However, a different behaviour was seen with some polymers, where the c.o.f. at an intermediate speed increased slightly from its value at a lower speed and then decreased when speed was increased. Figure 5.12 {B} shows the same behaviour at a lower roughness and the wear and friction results were similar to that at a roughness of 0.26 micron. In this case, for PVC and polycarbonate the c.o.f. decreased with an increase in sliding speed and the c.o.f. of all other polymers varied when speed was increased.

Comparing the graphs shown in Figures 5.11 and 5.12 it is seen that the wear volume and c.o.f. is different for different counterfaces for the same polymer under similar operating conditions. This suggests that the material of the counterface may have an effect on the wear and friction behaviour of some of the polymers tested.

(iii) LOAD:

Figures 5.13 and 5.14 show the wear and friction of different polymers tested at loads of 90 and 135N when sliding against AISI 1018 and HTSR 4140 counterfaces at roughnesses of 0.26 micron {A} and 0.13 micron {B}. From Figures 5.13 and 5.14 it can be seen that the wear volume increased with an increase in load, as expected.

From Figure 5.13 {A} at a roughness of 0.26 micron for AISI 1018 steel it can be seen that with increase in load there is not much of an increase in the wear volume for foulton and rulon when compared to other polymers where a considerable increase occurred. The c.o.f. remained the same for foulton and rulon but varied for all other polymers with an increase in load. The wear of most of these polymers at a lower roughness of 0.13 micron shown in Figure 5.13 {B} is similar to that at a higher counterface roughness as in {A}. An increase in wear volume was observed for all polymers except for rulon which remained the same with an increase in roughness. The c.o.f. varied with increase in load for all polymers except for rulon and LDPE.

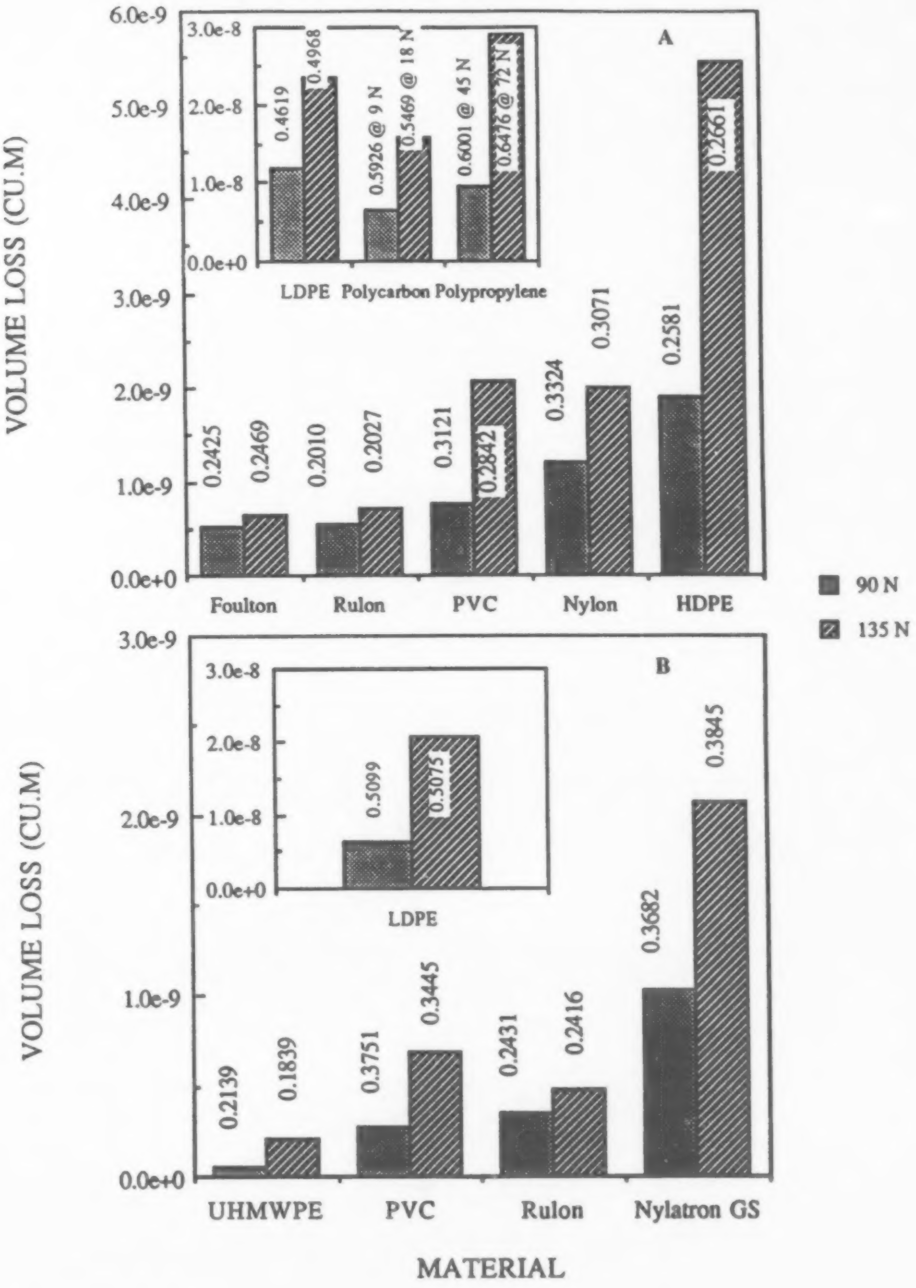


Fig. 5.13: Wear volume and Coefficient of friction of different polymers with normal load against AISI 1018 steel at different counterface roughnesses {A}: 0.26 microns; {B}: 0.13 microns; speed = 0.5 m/s, duration = 5 hours

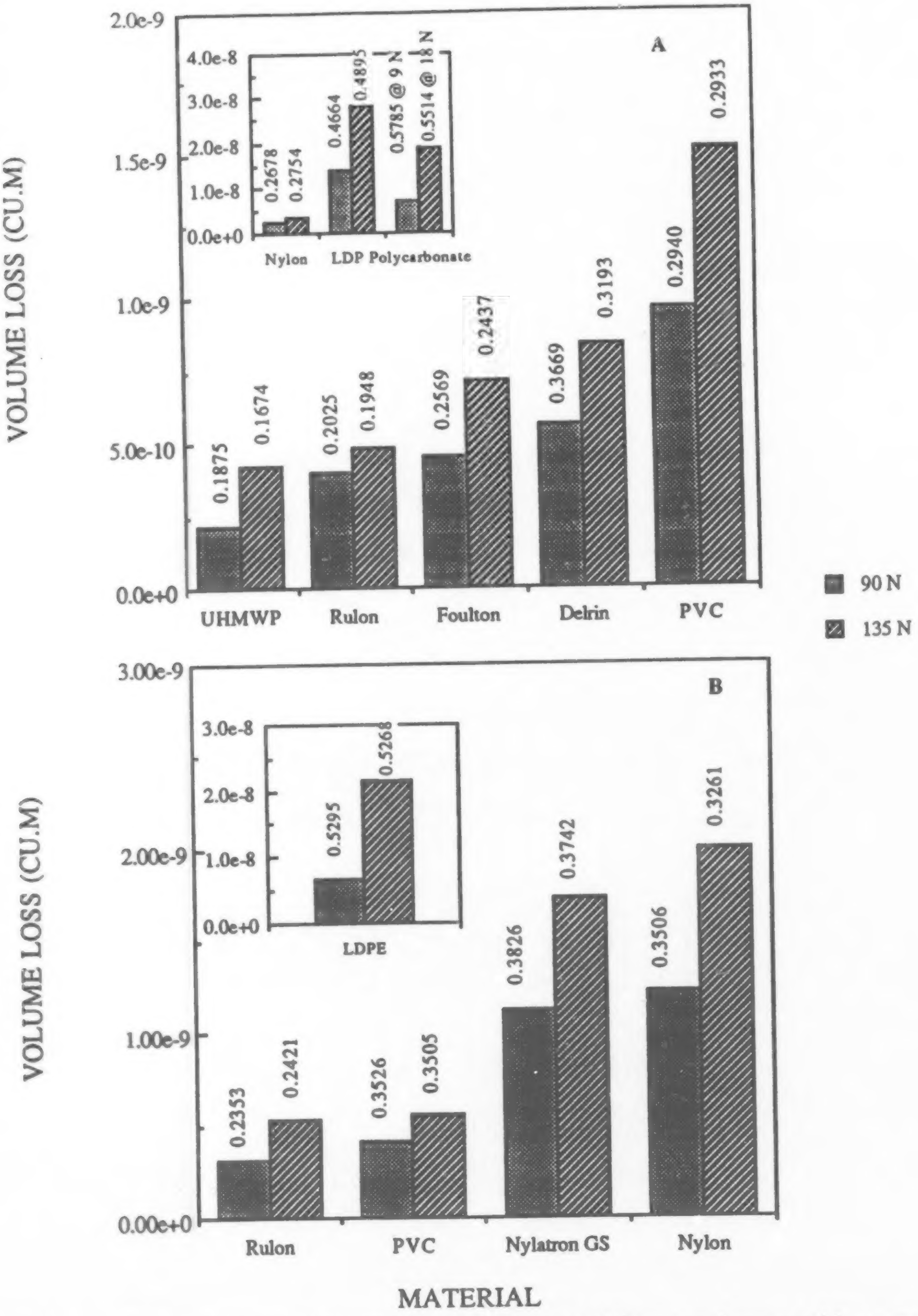


Fig. 5.14: Wear volume and Coefficient of friction of different polymers with normal load against HTSR 4140 steel at different counterface roughnesses {A}: 0.26 microns; {B}: 0.13 microns; speed = 0.5 m/s, duration = 5 hours

At a higher roughness of 0.26 micron shown in Figure 5.14 {A} for HTSR 4140, LDPE had the highest rate of increase in wear, whereas rulon showed the least increase in wear with an increase in load. For an increase in load the c.o.f. decreased for all materials except nylon and LDPE for which the c.o.f. increased, and the values remained the same for PVC. A similar behaviour was seen with materials sliding at a lower roughness of 0.13 micron shown in Figure 5.14 {B}. At this roughness, nylon, nylatron GS and LDPE showed a considerable increase in wear volume with an increase in load compared to other polymers. The c.o.f. of most polymers varied and were different from the case at higher roughness as shown in Figure 5.14 {A}.

From the above graphs shown in Figures 5.13 and 5.14 it is seen that wear increased with an increase in load and surface roughness as expected, but the variation of c.o.f. was inconsistent with some polymers at different loads. It was also observed that a decrease in the c.o.f. occurred with an increase in the counterface roughness for some of the polymers which was also observed from tests on the horizontal pin-on-disk machine. Again, the material of the counterface seem to have had an effect on the wear and friction characteristics of polymers.

5. 3. COMPARISON OF THE WEAR AND FRICTION BEHAVIOUR IN BOTH PIN-ON-DISK CONFIGURATIONS

The results obtained from both pin-on-disk configurations demonstrated the effect that different operating factors had on the wear and friction behaviour of polymers. In the horizontal pin-on-disk machine, operating variables such as load, speed, test duration, and counterface roughness were varied. For the vertical pin-on-disk machine, the variables were rpm or radius of the disk, surface speed, counterface roughness and load. The wear and friction phenomena that occurred for both configurations was observed to be the same under similar operating conditions.

A comparison of results of the wear volume and c.o.f. (tabulated in Appendix 3: Table A.3.25.) is shown in Figure 5.15. In both configurations an increase in load, speed, time, and counterface roughness resulted in an increase in wear. But the friction varied slightly with load and time; the friction increased with an increase in sliding

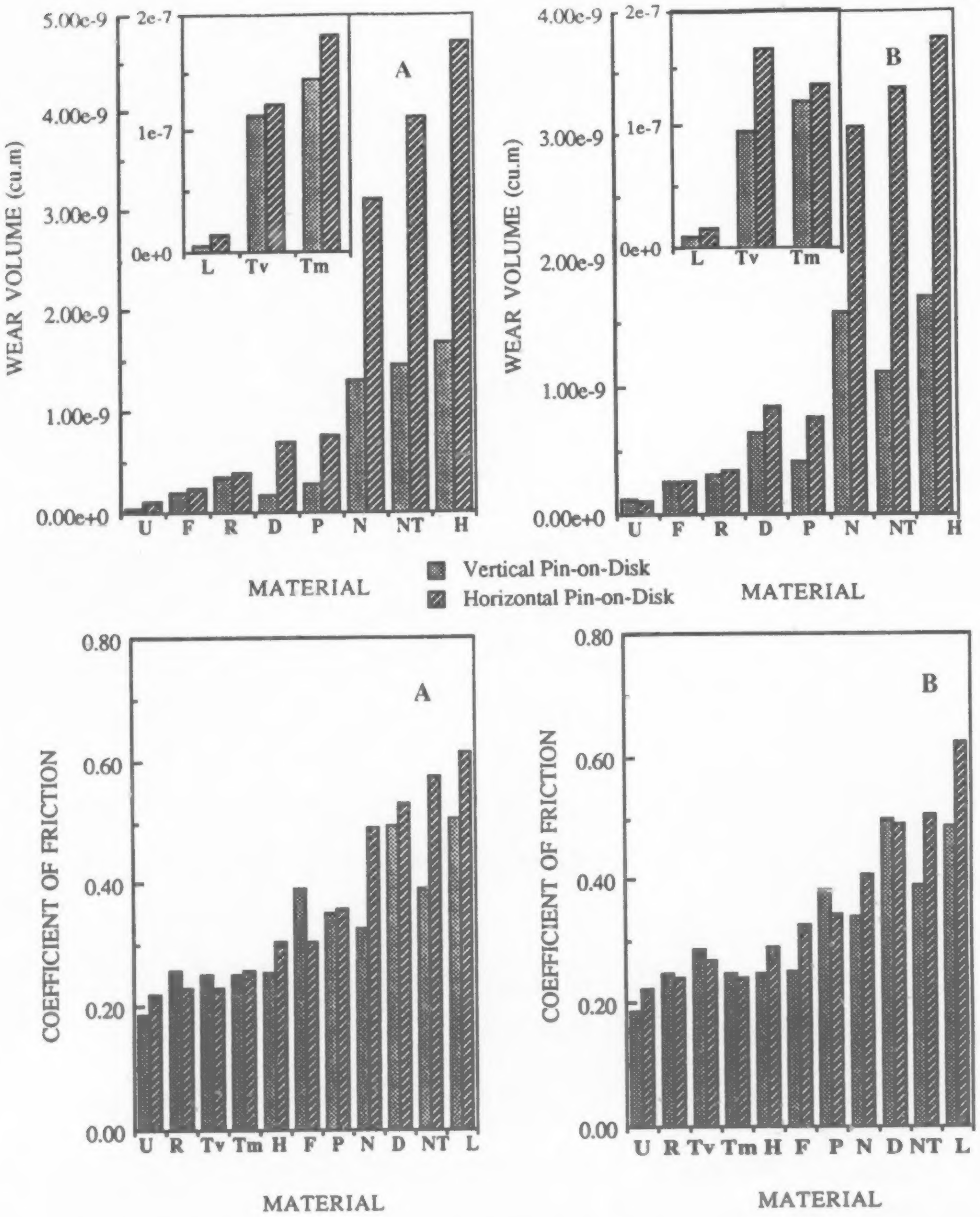


Fig. 5.15: Comparison of wear volume and coefficient of friction of different polymers sliding against AISI 1018 steel and HTSR 4140 steel counterfaces on horizontal pin-on-disk and vertical pin-on-disk configurations

{A}: AISI 1018 STEEL; {B}: HTSR 4140 STEEL

D-Delrin; F-Foulton; H-HDPE; L-LDPE; N-Nylon; NT-Nylatron; P-PVC; R-RULON; Tv-Teflon (v); Tm-Teflon(m); U-UHMWPE speed, and decreased with an increase in counterface roughness. The influence of the material of the counterface on the wear and friction behaviour of polymers was observed in both configurations. Overall, the only major difference was in the configuration of the testing equipment, which was responsible for quantitative differences in results of wear and friction. The comparative order of wear was approximately the same for both configurations with few exceptions as can be seen in Figure 5.15. It was found that the wear from the vertical pin-on-disk machine was always slightly less than the wear obtained in the horizontal pin-on-disk machine, but the c.o.f. varied for both pin-on-disk configurations without any specific behaviour. The reason for this might be because of the degree of control in the operating temperatures attained during the tests due to constraints in the testing configurations. In the case of the vertical pin-on-disk configuration the counterface disk temperature was controlled by conduction between the disk and water circulated copper tubing which was effective in maintaining the counterface contact at ±2 °C of room temperature. Whereas in the case of the horizontal pin-on-disk machine, the counterface contact temperature was controlled by convection using a cooling fan which was only effective in maintaining the contact at -2 to +8 °C of room temperature. The scatter in the wear results of the horizontal pin-on-disk machine are also attributed to fan blowing off some wear debris, which did not occur in vertical pin-on-disk machine as the debris stayed on the flat surface of the disk.

Figure 5.15 (Table A.3.25 in Appendix 3) confirms that the material of the counterface has similar influences on the wear and friction behaviour of polymers in both the pin-on-disk configurations. But there is a difference in the two pin-on-disk operating systems and the wear and friction behaviour of the polymers tested show the influence of the testing configuration. The major differences between the two systems being that one has a flat wear contact surface and the other has a curved wear contact surface.

5. 4. ANALYSIS AND COMPARISON OF DIFFERENT WEAR BEHAVIOURS FROM THE SCANNING ELECTRON MICROGRAPHS

In many tribological systems one or more wear mechanisms can occur. A fundamental understanding of the wear process needs to be obtained in order to develop an appropriate analytical model. To assist in this understanding the appearance of worn surfaces may indicate which wear mechanism occurred. Subsurface features are an important aspect of the wear analysis and the SEM technique has provided an useful tool in assessing the micro topography of the worn surfaces. Because of the destructive nature of the process and the objective of the study was analyzing the wear of polymers, micrographs were prepared on the polymer specimens only. In addition, a few micrographs of the counterfaces were selected to observe the wear track of the transfer of polymer on to the counterface. Different wear processes observed during the tests are reported below.

Adhesion, characterised by the transfer of polymer debris to the counterface, was seen in some cases with surface melting and sometimes in combination with abrasion. Similar wear behaviours were observed in HDPE, rulon, teflon(v), LDPE, polypropylene and nylon sliding against AISI 1018 and HTSR 4140 counterfaces, in the range of 90 - 145N load, 0.25 - 0.5 m/s speed, 5 - 25 hours test duration and 0.08 - 0.12 micron counterface roughness.

Abrasion was observed as grooves, valleys and cracks on the surface. Abrasive wear was clearly seen in the form of gouging, ploughing, surface fracture, and contaminant interaction in a few cases during sliding against rough surfaces resulting in severe deformation of the polymer surface. These were commonly seen with polymers such as, teflon(m), PVC, delrin, UHMWPE, LDPE and nylatron GS at higher counterface roughnesses greater than 0.13 micron under the conditions, 90 - 145N load, 0.25 - 0.5 m/s speed and 5 - 25 hours test duration (except for teflon(m) tested at lower ranges). From additional micrographs observed (not shown here) sometimes abrasion was also seen in combination with the fatigue process.

The formation of thin laminated sheets and delamination wear was predominant for some of the polymers with the failure of the surface and transfer of polymer fragments in the form of sheets. This type of wear was commonly observed in polymers such as, teflon(v), teflon(m) and PVC at low sliding speed of 0.125 m/s, 90 - 145N load, 2 - 5 hours test duration and 0.1 - 0.12 micron counterface roughness. From additional micrographs observed (not shown here) sometimes delamination was also seen in combination with other wear processes like adhesion.

Fatigue failure leading to pits, spalls or cracks on the surface was seen in a few cases. The fatigue wear process was observed in cases where the counterface roughness was higher than 0.16 micron and other conditions were in the range of 90 - 145N load, 0.5 m/s speed and 5 - 10 hours test duration. This was seen for polymers such as, LDPE, nylatron GS, delrin, PVC and foulton. From additional micrographs observed (not shown here) sometimes fatigue was also seen in combination with abrasion.

Due to the limitation of temperature generated in the polymer surface from the SEM equipment and the large number of tests conducted, similar polymers have not been compared at similar magnification and/or operating conditions. But most of these behaviours explained here were observed in the polymers tested.

Plate 1 {Figures 1 - 6} shows the adhesive wear observed for different polymer surfaces. From Figures 1-2 it can be seen that adhesive junctions have been formed and small layers have been sheared to release wear debris. In Figures 3-4 debris released as loose wear fragments attached to the worn surface can be seen along with junctions about to rupture. Figures 5-6 show surfaces which have undergone adhesive wear along with plastic deformation and partial surface melting. Sheared layers caused plastic flow of the surface resulting in the release of the wear fragments.

Plate 2 {Figures 7 - 12} shows abrasive wear characteristics of some of the polymer worn surfaces. Figure 7 shows a crater formed due to gouging which occurred when the softer material surface was gouged by a harder asperity of the counterface. Figure 8 shows a partial abrasion of the contact surface with abrasive features continuing to cover the entire contact region. Here the abraded surface is seen along with the wear debris being removed. Figures 9-10 show abrasion over the entire contact surface area due to ploughing by a rough counterface. Also, indentation of the asperities and a plough track of the counterface profile forming ripples on the worn surface of the

PLATE 1: *Adhesive Wear of Polymers*

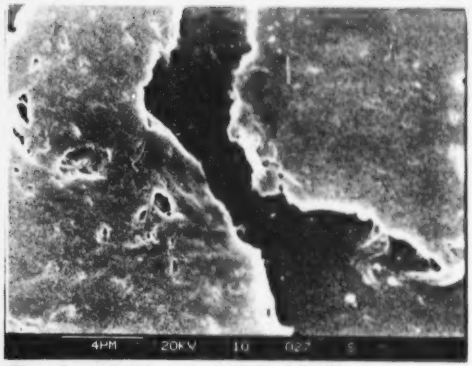


Fig. 1 *HDPE vs. MILD STEEL*
88.96 N, 0.5 m/s, 5 hrs,
0.12 microns. 3000x

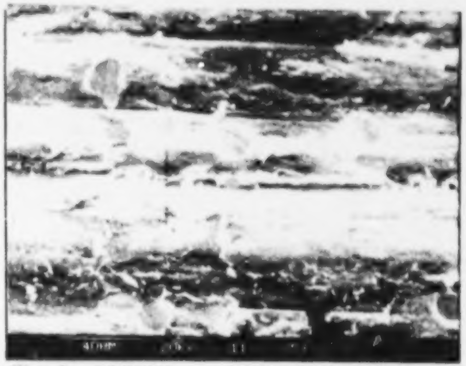


Fig. 2 *RULON vs. HTSR 4140 STEEL*
88.96 N, 0.375 m/s, 5 hrs,
0.12 microns. 325x

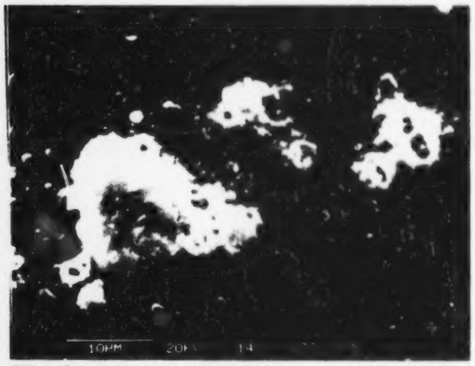


Fig. 3 *POLYPROPYLENE vs. MILD STEEL*
88.96 N, 0.1 m/s, 5 hrs,
0.1 microns. 1300x

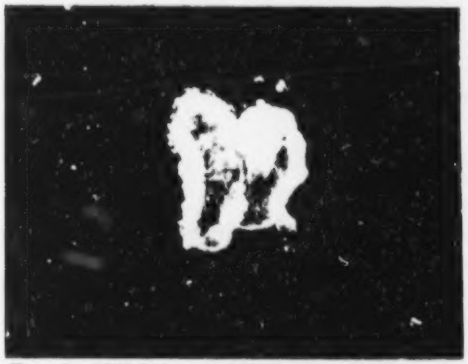


Fig. 4 *NYLON vs. HTSR 4140 STEEL*
88.96 N, 0.5 m/s, 5 hrs,
0.15 microns. 650x

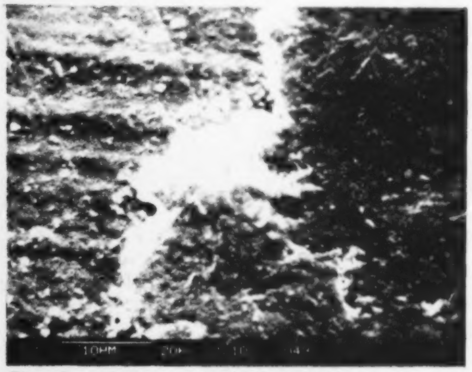


Fig. 5 *HDPE vs. MILD STEEL*
142.34 N, 0.5 m/s, 5 hrs,
0.13 microns. 1300x

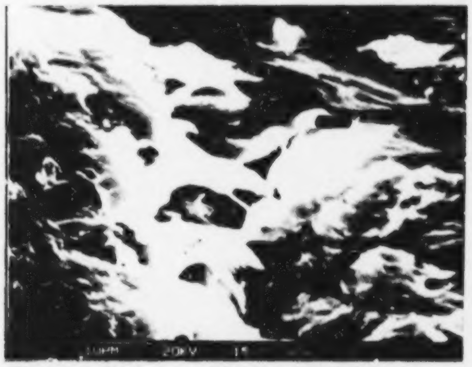


Fig. 6 *LDPE vs. HTSR 4140 STEEL*
106.76 N, 0.5 m/s, 5 hrs,
0.15 microns. 1300x

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* MILD STEEL: AISI 1018 STEEL

PLATE 2: *Abrasive Wear of Polymers*

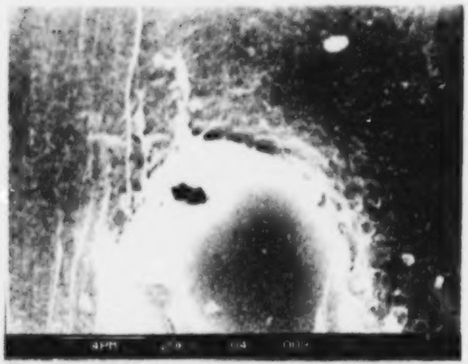

Fig. 7 TEFLON (M) vs. MILD STEEL
88.96 N, 0.5 m/s, 100 min,
0.05 microns. 3125x

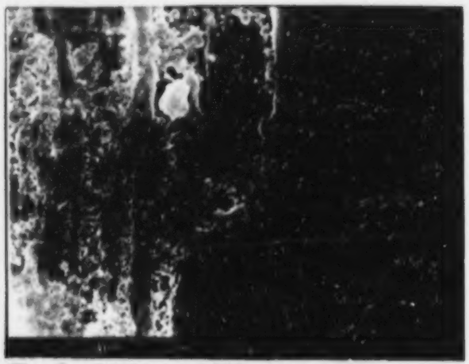

Fig. 8 PVC vs. HTSR 4140 STEEL
88.96 N, 0.375 m/s, 5 hrs,
0.16 microns. 3125x

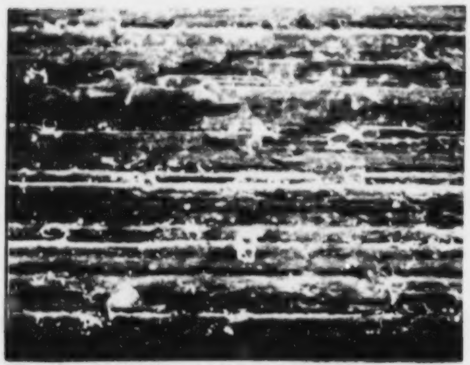

Fig. 9 RULON vs. MILD STEEL
88.96 N, 0.5 m/s, 25 hrs,
0.14 microns. 125x

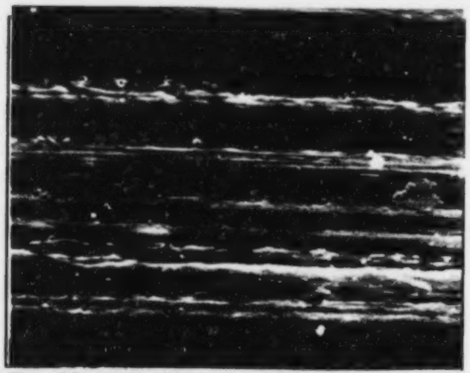

Fig. 10 UHMWPE vs. MILD STEEL
88.96 N, 0.5 m/s, 125 hrs,
0.25 micron. 800x

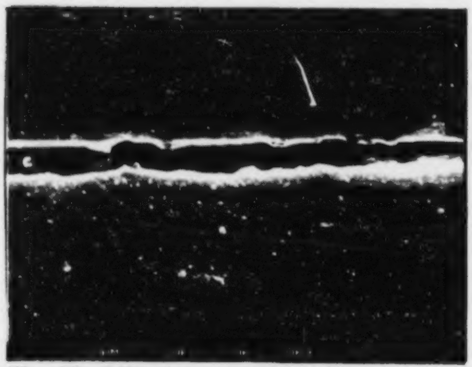

Fig. 11 DELRIN vs. MILD STEEL
88.96 N, 0.5 m/s, 5 hrs,
0.35 microns. 1300x

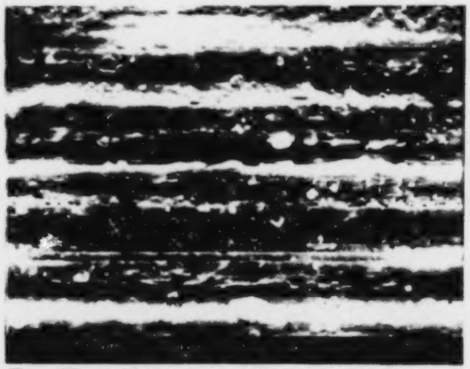

Fig. 12 DELRIN vs. HTSR 4140 STEEL
88.96 N, 0.25 m/s, 5 hrs,
0.17 microns. 1400x

*** MILD STEEL: AISI 1018 STEEL**

polymer is shown. Figure 11 shows a typical single sharp point rough metal counterface asperity which has caused deep ploughs in the polymer surface. Other regions on this worn surface have undergone mild abrasive wear with some wear debris released as tiny particles. Figure 12 shows a fully abraded surface due to ploughing with some fatigue cracks being formed on the surface. The abraded polymer surface shows gouging of the rough counterface and crack formation leading to the release of wear fragments.

Plate 3 {Figures 13 - 15} shows the delamination that occurred in some of the polymers at the contact region resulting in wear debris in the form of sheets. The layer in Figure 15 which is sheared from the parent material, can be seen curled and in the process of detaching from the surface as a debris in the shape of a delaminated sheet.

Plate 3 {Figures 16 - 18} shows the fatigue wear process that was observed. Figure 16 shows typical fatigue micro cracks formed on a delrin surface which were seen to propagate on the surface leading to the release of wear fragments. Figure 17 shows fatigue cracks formed on the severely abraded surface of a LDPE specimen in the direction of sliding which caused deformation resulting in the release of wear fragments. Figure 18 shows a foulton surface which had undergone a fatigue failure resulting in shearing of the junction and crack formation leading to the release of wear debris.

Plate 4 {Figures 19 - 24} shows some different wear features observed on the polymer and metal counterface after the sliding. Figure 19 shows a back-scattered image of a rulon surface with some contamination and the presence of traces of metal particles. The x-ray analysis of the surface showed traces of silicon and iron. Contamination while preparing the specimen for SEM may be the reason for these particles, although the exact reason is unknown. The dark patches seen on the surface were detected to be metal particles embedded on the polymer surface. A clear and severe deformation of the surface of the polymer can be seen. This feature was typical of rulon (a ceramic filled fluorocarbon) while sliding against both AISI 1018 and HTSR 4140 counterfaces. Figure 20 shows a metal crystal formation on the worn surface of HDPE. The x-ray analysis revealed the presence of iron and silicon, which again is of unexplained origins. The structure may also be due to the contamination trapped at the contact junction. These crystals were found only at some discrete points on the surface of the polymers, such as

PLATE 3: Delamination and Fatigue Wear of Polymers

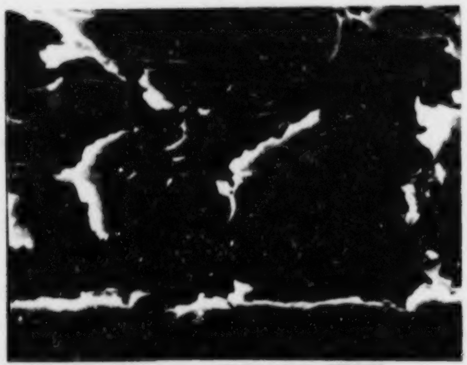

Fig. 13 PVC vs. HTSR 4140 STEEL
142.34 N, 0.5 m/s, 5 hrs,
0.15 microns. 1300x

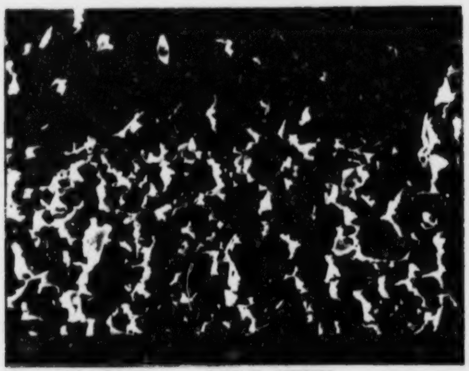

Fig. 14 PVC vs. MILD STEEL
88.96 N, 0.125 m/s, 5 hrs,
0.12 microns. 130x

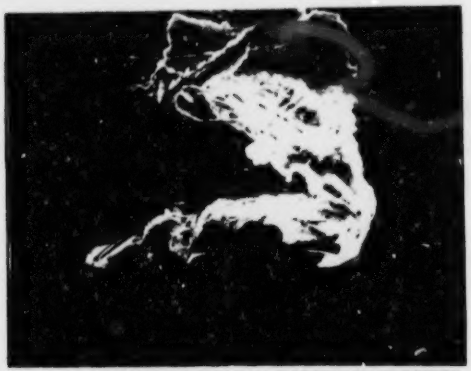

Fig. 15 TEFLON (M) vs. HTSR 4140 STEEL
88.96 N, 0.125 m/s, 100 min,
0.125 microns. 325x

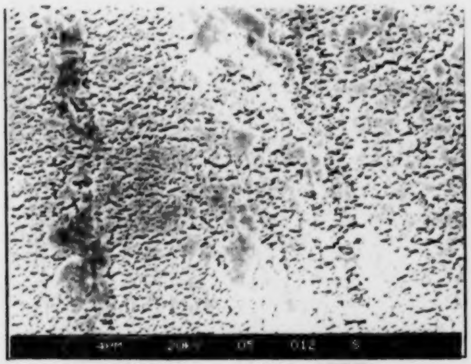

Fig. 16 DELRIN vs. MILD STEEL
88.96 N, 0.5 m/s, 5 hrs,
0.2 microns. 3125x

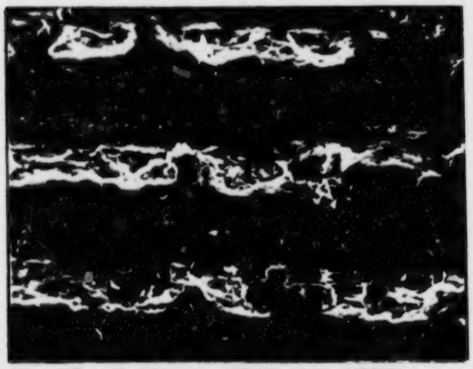

Fig. 17 LDPE vs. HTSR 4140 STEEL
106.76 N, 0.5 m/s, 5 hrs,
0.18 microns. 130x

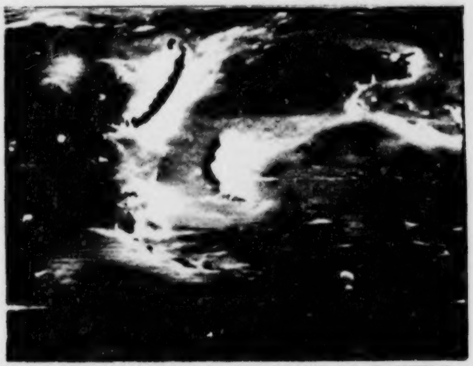

Fig. 18 FOULTON vs. HTSR 4140 STEEL
133.44 N, 0.5 m/s, 5 hrs,
0.195 microns. 1300x

*** MILD STEEL: AISI 1018 STEEL**

PLATE 4: Special Wear Features of Polymer Surface and Counterface Topography after the Wear

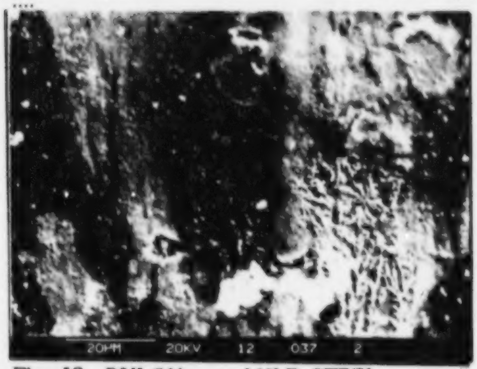

Fig. 19 RULON vs. MILD STEEL
88.96 N, 0.5 m/s, 5 hrs,
0.14 microns. 650x

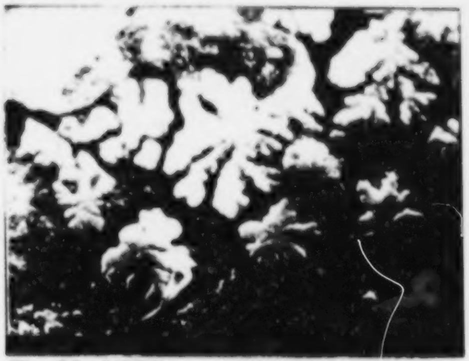

Fig. 20 HDPE vs. HTSR 4140 STEEL
88.96 N, 0.5 m/s, 25 hrs,
0.125 microns. 1300x

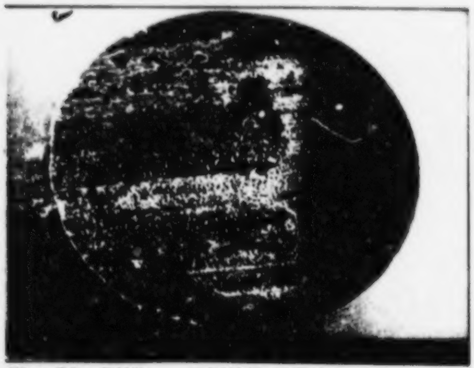

Fig. 21 PVC vs. MILD STEEL
88.96 N, 0.125 m/s, 5 hrs,
0.118 microns. 10x

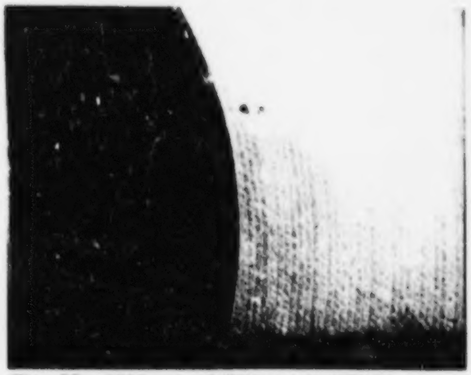

Fig. 22 PVC vs. HTSR 4140 STEEL
142.34 N, 0.5 m/s, 5 hrs,
0.15 microns. 25x

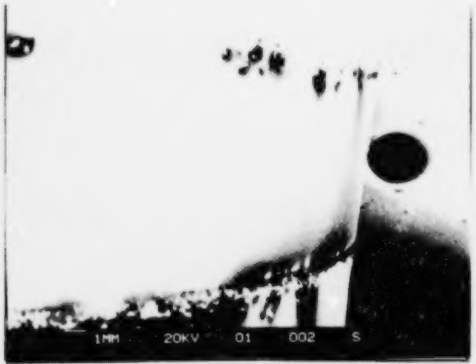

Fig. 23 HTSR 4140 STEEL vs. HDPE
88.96 N, 0.5 m/s, 5 hrs,
0.112 microns. 3x

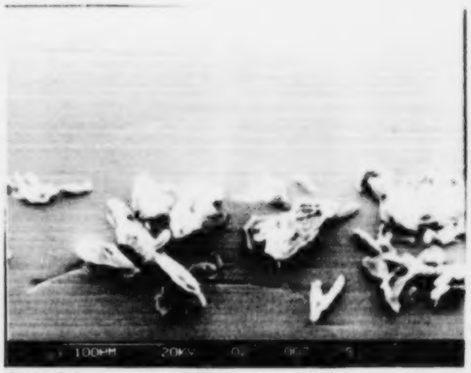

Fig. 24 MILD STEEL vs. PVC
88.96 N, 0.5 m/s, 5 hrs,
0.08 microns. 155x

*** MILD STEEL: AISI 1018 STEEL**

HDPE and rulon. Figure 21 shows both worn and unworn structure of a polymer surface at contact, observed at a low sliding speed. This picture clearly shows that, initially, the contact was over a partial area and then with the progress of time the contact occurred over the entire surface, thus causing mild wear. The partially worn surface shows a typical abrasive wear due to tearing of the surface and the debris released on the surface. Figure 22 shows a surface with both worn surface and the machined truncated cone region. The direction of sliding and the wear tracks can be seen on the worn surface along with the wear region progressing towards the unworn machined surface.

Figures 23-24 shows the micrograph of metal counterfaces after the wear test. In Figure 23 wear tracks from the polymer wear debris on the surface of the metal counterface can be seen. The two streaks of polymer wear debris attached to the surface was the width of the wear track during sliding (area of the polymer pin in contact with the metal counterface). The wear debris adhered to the counterface confirms the transfer of the softer polymer to the harder metal. In Figure 24 bulk wear debris of the polymer transferred to the counterface can be seen in the form of flakes in addition to the counterface topography. There was no change in the roughness value of the counterface before and after the test, but certainly the profile of the surface topography changed after the sliding.

6. CONCLUSIONS AND RECOMMENDATIONS

The type and extent of wear in polymers is determined by the nature and properties of the materials and the operating conditions. There are no universal theories governing wear, and the variety of conditions which in combination are responsible for wear, complicates the analysis. Nevertheless, the increased use of polymers in industrial applications requires a better understanding of their wear behaviour under a variety of operating conditions.

The main aim of this research was to obtain a reliable correlation between various factors influencing the wear behaviour of polymers in different conditions and applications. An empirical mathematical model in the form of a wear equation was developed for a better understanding of the overall wear behaviour and response to specific operating conditions.

6. 1. CONCLUSIONS

Following are the observations and conclusions of this research.

1. The main objective of the research to establish an equation for the wear of polymers involving operating variables and material properties was achieved using the technique of dimensional analysis. It was shown that the variables could be reasonably represented by five dimensionless groups.
2. A comparison of a linear and a non-linear relationship of volume loss of polymers with operating variables was made. The analysis showed that the wear volume was better represented by an exponential proportionality with the operating variables.
3. From sensitivity and uncertainty analysis, the exponential form of wear equation was found to be more appropriate than the linear form.
4. Different orders of magnitude of the wear coefficients for different polymers obtained from the exponential model confirmed that the material properties and non-linear relation of volume loss to operating variables influence the wear coefficient. This was not seen in the case of the linear model as it did not

involve all the material properties that were found to influence the wear process. Thus, the magnitude of the wear coefficient determined by the exponential model better represented the wear potential of the polymers tested.

5. The wear coefficients found from the exponential model had less percentage error than the linear model. The sensitivity of the wear coefficients with operating variables was less in the case of exponential model, which justified that these wear coefficients are constants for a given polymer-metal pair.

6. The operating variables had an expected influence on the wear and c.o.f. for polymers with few exceptions typical to some polymers. In general the following features were observed;

(i) Higher loads caused an increase in wear and the c.o.f. varied with load for some of the polymers tested.

(ii) The wear volume and c.o.f. for most polymers increased sharply with speed.

(iii) With an increase in duration of tests (i.e., with sliding distance) the wear of polymers increased, and significant wear was observed for longer test durations. The c.o.f. varied with sliding time during the test for some polymers.

(iv) Surface finish of the counterface had an effect on the amount of wear and c.o.f. during sliding. Higher counterface roughness increased the wear and decreased the c.o.f. for polymers. During sliding, polymers transferred to the counterface, changing the surface profile but not the surface roughness of the counterface.

(v) Counterface cooling during the tests was observed to be effective in reducing the wear volume and c.o.f.

(vi) At constant surface sliding speed the wear volume and c.o.f. approximately remained the same for most polymers. Therefore, rpm of the disk or number of traverses on the wear track was not significant on the wear volume and c.o.f.

7. The configuration of the experimental apparatus had an influence on the wear and friction behaviour of polymers tested.

8. For each polymer, the wear volume and c.o.f. was found to vary with the counterfaces under specific operating conditions. The behaviour observed emphasised the fact that counterface material influenced the wear and friction of polymers.

6. 2. RECOMMENDATIONS

The results of this research has identified some additional areas where further research is warranted.

1. The influence of the counterface material has to be considered in more detail. In addition, the influence of machine surface lay, hardness and material composition needs to be separately evaluated.
2. Some of the differences in the wear and friction results may be eliminated by conducting the experiments in a constant humidity chamber or under vacuum conditions.
3. The natural distribution of the wear coefficients and hence the wear behaviour into two groups of the polymers tested suggests that there may be some relationship between the molecular structure and the wear resistance. This should be investigated in more detail as this may lead to a more generalized wear model.

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APPENDIX 1

A. 1. WEAR TESTING MACHINES, PREPARATION OF SPECIMEN AND DETAILED EXPERIMENT PROCEDURE

A. 1. 1. DESCRIPTION OF THE HORIZONTAL PIN-ON-DISK MACHINE:

The configuration of the machine is shown in Figure A.1.1. This machine was developed from a ASTM G-65 standard rubber abrasion tester. The machine has disks of 100mm diameter and 12.5mm thick, made of both cold rolled AISI 1018 and HTSR 4140 steel mounted to the horizontal shaft spindle of a motor using a friction assembly and a bolt. The speed of the disk can be controlled in the range 0-300 rpm. The polymer pin is mounted in a special load cell which in turn is clamped to a fixture which

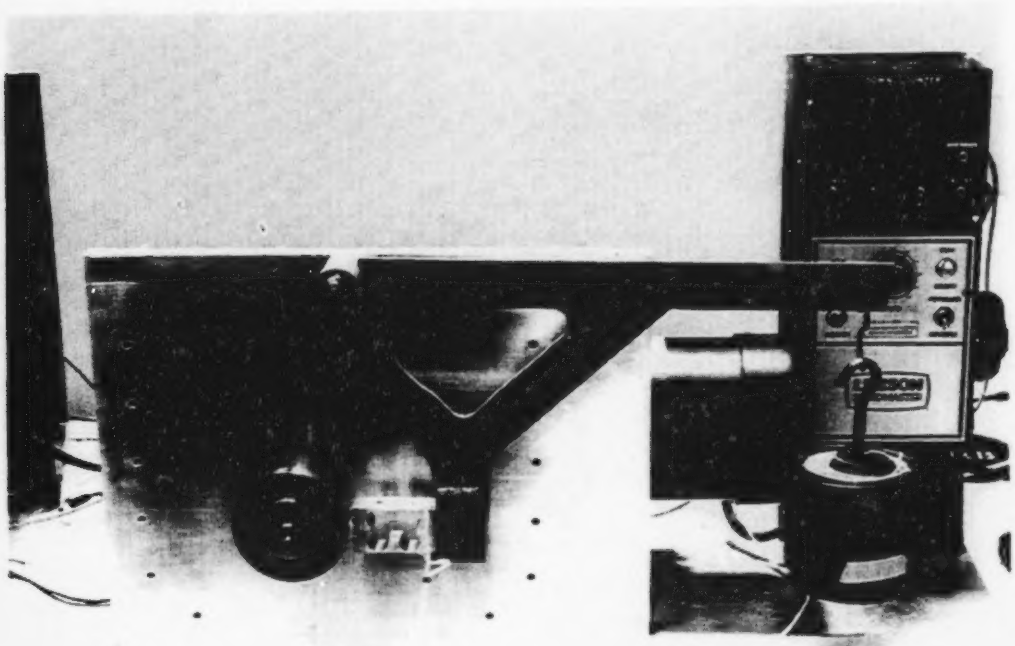

Fig. A.1.1 : Horizontal pin-on-disk machine

applies load to the specimen in contact with the steel disk. The fixture has a moment arm of 1:2 for the application of load which is hung from a hook at the end of the moment arm. A sealed bearing in the fixture transfers the entire load on to the specimen with negligible losses. The special load cell and strain gauge conditioner measures the tangential force which is recorded on a plotter. For a given rpm of the disk the polymer pin is loaded against the rotating rim of the disk. The total number of revolutions for the test can be preset on a timer which automatically stops the test after the number of revolutions has been completed. This is known as a horizontal pin-on-disk machine because the pin axis is horizontal and crossed with respect to the axis of disk rotation.

A. 1. 2. DESCRIPTION OF THE VERTICAL PIN-ON-DISK MACHINE:

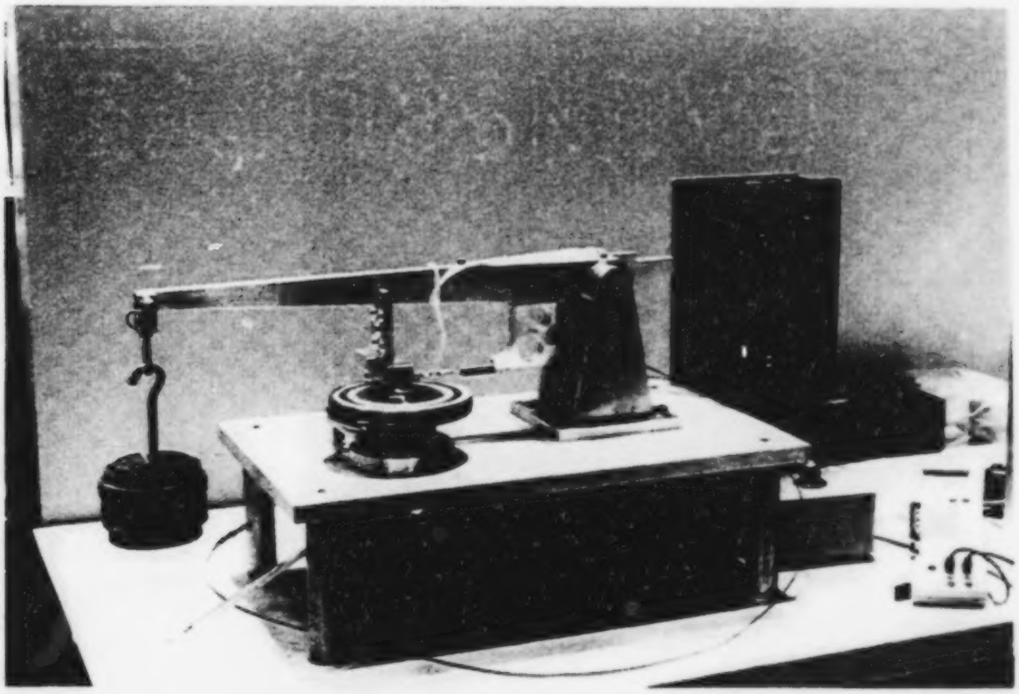

Fig. A.1.2 : Vertical pin-on-disk machine

The vertical pin-on-disk machine shown in Figure A.1.2 is typical of many wear testing machines where a vertical pin held through a pin holder attached to the loading arm is loaded against the flat surface of a horizontal disk. The steel disks are machined from cold rolled AISI 1018 and HTSR 4140 steel and are 150mm in diameter and 12.5mm thick. The specimen holder is connected to a tensile load cell which measures the tangential force similar to the horizontal pin-on-disk machine. The vertical pivoted arm supports the specimen holder and transfers the load on to the polymer pin/metal junction. The loading arm is 1:2 in proportion for the application of load, hung from a hook attached at the end of the moment arm. The loading arm can slide in the slots to the required radius measured on a scale attached on the machine. The disk rotates at a given rpm at a specific radius of the disk, maintaining the required surface speed constant. This is known as vertical pin-on-disk machine, because the pin axis is vertical and parallel with respect to the axis of disk rotation.

As a special feature of this machine, the flat steel disk is lined with copper tubing on the bottom side for circulating cold water to maintain the disk approximately at laboratory room temperature throughout the test. The copper tubes are connected to an inlet and an outlet in the cooling jacket which is mounted with the steel disk making the entire unit an integral part. The number of revolutions or duration of test can be preset on the motor and the test stopped after the elapsed number of revolutions. A laboratory set up of both machines during testing is shown in Figure A.1.3.

A. 1. 3. PREPARATION AND MOUNTING OF THE POLYMER PIN SPECIMEN:

Polymer specimens were machined as cylindrical pins with a truncated cone at one end as shown in Figure 4.1 which is a common pin geometry in many research investigations. These pins were made on a computer controlled lathe using a 9.5mm extruded rod of polymer. A high dimensional accuracy was achieved and therefore all the pins were of identical shape and configuration. Identical properties were also obtained because all the pins of each polymer were made from a single extruded rod. The conical end was a truncated cone, 3.75mm in diameter, which provided a surface area of 10-12mm^2. This enabled the initial surface to wear out fast, thus not affecting further bulk wear. A good representation of weight loss could also be obtained because of the small area being in contact. The larger cylindrical end furnished bulk strength

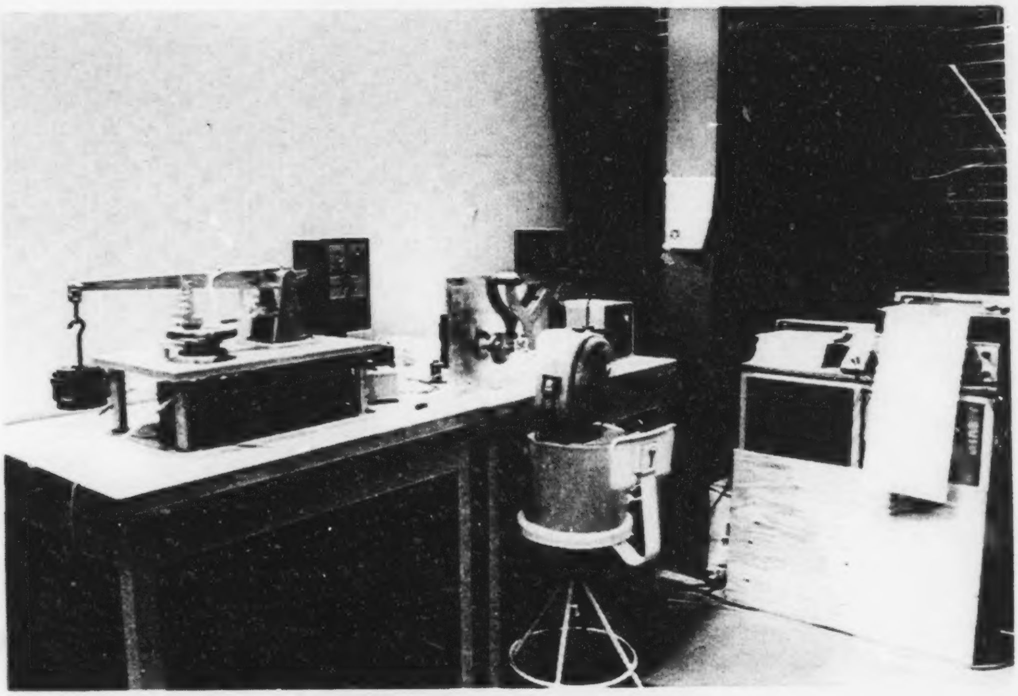

Fig. A.1.3 : Experimental set up in the laboratory showing both the Horizontal and the Vertical pin-on-disk machine

support to the smaller end of the specimen in contact with the rotating disk against deformation and distortion under load. The conical end of the pin surface was polished on a fine emery paper (grade 600 grit size) to remove machined debris. The pins were washed in methanol and dried with compressed air. They were weighed on an electronic balance to an accuracy of ±0.0001 grams.

Prior to a test the pin was mounted in the specimen holder which was part of the load cell. The pin surface was once again wiped with methanol to get rid of contamination and was cleaned with a cotton ball and dried with compressed air. The same steps were carried out for a control sample specimen which was weighed before the test and kept alongside the machine to evaluate the effects of humidity, if any.

A. 1. 4. DETAILED EXPERIMENTAL PROCEDURE:

(i) TESTING ON THE HORIZONTAL PIN-ON-DISK MACHINE:

The steel disks were ground on an automatic grinder to maintain the surface true (i.e., circular). Then the steel disks were polished on a lathe using standard emery paper of different grades (240, 320, 400, and 600 grit size) to get the required surface roughness. Surface roughness of the disk was measured on a Taylor Hobson Talysurf-4, where the centre line average (c.l.a.) and surface profile were obtained. The c.l.a. value in micro-inches was recorded at different positions on the rim of the disk on both sides. The average of all c.l.a. values in measured in micro-inches was taken as the counterface roughness and was converted to micro-meters (micron). Since it was a friction assembly with a bolt, the disk surface was checked with a dial gauge to ensure that it would rotate perfectly true. The steel disk surface was first wiped with acetone to dissolve and take away all contaminants on the surface, then it was cleaned with methanol to absorb any moisture and dust. Finally, a clean cotton ball was used to wipe the surface and dried with compressed air. The polymer pin specimen was mounted in the specimen holder. The motor was set for a particular speed and the required number of revolutions. The strain gauge conditioner and plotter were checked and stabilized. Once the initial set up was complete the motor was switched on for disk rotation (clockwise) and the loading arm was slowly released so that the polymer pin contacted the rotating disk surface and the load was gradually applied.

Humidity as measured by a sling psychrometer and temperature in the laboratory were noted. The tangential force was recorded on the plotter and the multimeter reading in millivolts representing tangential force were also noted. At regular intervals the speed was checked and stabilized and multimeter readings were recorded. A cooling fan was used to maintain the temperature of the surface of the counterface during the test so that the temperature at the junction did not become too high to cause polymer surface melting. The temperature was regulated at -2 to +8°C from room temperature throughout the test, thus avoiding high temperature effects on the wear behaviour. At the end of the test, humidity and temperature in the laboratory were noted. Variation in the humidity and temperature in the laboratory during the test were compared and approximately the same conditions were chosen for repeating the tests. The difference in the weights of the specimen before and after the test was the amount of wear of the polymer under given operating conditions. The control pin was weighed after the test to check for any moisture variations. The change in weight the control pin due to humidity changes were assumed to be similar to those of the test specimen. This minimized any possible effects such as humidity, temperature, etc., on the repeatability in weighing. All these data were recorded in a spread sheet and volume loss was calculated from the density of the polymer. All the tests were repeated three to four times for reproducibility of results. After a test was completed the steel disk was polished again and it was prepared for the next test.

(ii) TESTING ON THE VERTICAL PIN-ON-DISK MACHINE:

The testing procedures were similar to those used for the horizontal pin-on-disk machine. The steel disks were ground on an automatic grinder. The required surface roughness was obtained through grinding (no polishing). The surface roughness was measured on the flat surface radially perpendicular to the machine lay. A number of measurements were made to obtain an average value. The steel disk, which is an integral part of cooling jacket, was mounted on to the vertical spindle of motor through a morse taper after thoroughly greasing the seal assembly and outside of the cooling jacket to avoid corrosion. The polymer pins were mounted in the specimen holder attached to the load cell. The testing parameters were chosen and circulation of cooling water was started and the motor was switched on to begin the test. The specimen was slowly rested on the rotating horizontal disk and the load was gradually applied.

Laboratory room temperature and humidity, and rate of flow and temperature of the cooling water through the jacket were noted. During the test the temperature and rate of flow of cooling water was checked occasionally. After the completion of test, the laboratory room temperature and humidity were noted, and the specimen was removed and weighed. The difference in the weights was recorded and tabulated for further analysis. The steel disk was cleaned with acetone and methanol. Several tests were conducted for each specimen changing the radius of revolution by simply sliding the loading arm to the required position. A new specimen was mounted and the system was set ready for another test on the same disk. Tests were repeated for reproducibility of results. Six to nine tests could be run on the disk at different radii and operating variables for the same polymer, so that the complete disk surface was made use of before the steel disk was ground for another round of tests with a different polymer.

APPENDIX 2

A. 2. DIMENSIONAL ANALYSIS IN DEVELOPING THE WEAR EQUATION

The following factors are used in the development of the wear equation along with their (units) and [dimensions] in the brackets.

1. V - Volume of the polymeric material worn (m^3) - [L^3]
2. W - Normal load at the junction (N) - [MLT^{-2}]
3. T - Duration of test (s) - [T]
4. α - Counterface roughness (m) - [L]
5. v - Sliding speed (m/s) - [LT^{-1}]
6. E - Modulus of elasticity of the polymers (N/m^2) - [$ML^{-1}T^{-2}$]
7. γ - Surface energy (N/m) - [MT^{-2}]
8. C_p - Specific Heat (Cal/°C - Kg) - [$L^2T^{-2}\Theta^{-1}$]
9. K - Thermal conductivity (Cal/°C - m - s) - [$MLT^{-3}\Theta^{-1}$]

To carry out the dimensional analysis, the dependent variable wear volume V is grouped and expressed as

$$\Psi\,(V,W,T,\alpha,C_p,\gamma,E,v,K) = 0\ ,$$

where Ψ is some arbitrary function.

The four primary dimensions are mass(M), length(L), time(T) and temperature(Θ). The dimensional powers of all the variables were tabulated and listed under different factors such as k_1 to k_9 assigned for each variable as shown in Table A.2.1. The factors k_1 to k_5 assigned to volume(V), load(W), duration of test(T), counterface roughness(α) and specific heat(C_p) were considered as the primary variables and the factors k_6 to k_9 assigned to surface free energy(γ), modulus of elasticity(E), sliding speed(v) and thermal conductivity(K) were considered as secondary repeating variables. To obtain the dimensionless groups, the parameters of all the variables with their corresponding powers of the dimensions as coefficients were expressed in the form of equations as shown below which were solved for k_6 to k_9 in terms of k_1 to k_5.

TABLE A.2.1 : Dimensional powers of the variables

	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
	V	W	T	α	C_p	γ	E	v	K
M	0	1	0	0	0	1	1	0	1
L	3	1	0	1	2	0	-1	1	1
T	0	-2	1	0	-2	-2	-2	-1	-3
Θ	0	0	0	0	-1	0	0	0	-1

The following set of equations are written from the table A.2.1. and solved for the coefficients.

$$k_2 + k_6 + k_7 + k_9 = 0 \tag{i}$$

$$3k_1 + k_2 + k_4 + 2k_5 - k_7 + k_8 + k_9 = 0 \tag{ii}$$

$$-2k_2 + k_3 - 2k_5 - 2k_6 - 2k_7 - k_8 - 3k_9 = 0 \tag{iii}$$

$$-k_5 - k_9 = 0 \tag{iv}$$

From (iv)

$$k_9 = -k_5 \tag{1}$$

From (i)

$$k_6 + k_7 = -k_2 - k_9 = -k_2 + k_5$$

$$k_7 = -k_2 + k_5 - k_6$$

Now, substituting k_7 in (ii), we get

$$3k_1 + k_2 + 2k_5 - (-k_2 + k_5 - k_6) + k_8 - k_5 = 0$$

$$3k_1 + 2k_2 + k_4 + k_6 + k_8 = 0$$

$$k_8 = -3k_1 - 2k_2 - k_4 - k_6$$

Now from (iii)

$$-2k_2 + k_3 - 2k_5 - 2k_6 - 2(-k_2 + k_5 - k_6) - (-3k_1 - 2k_2 - k_4 - k_6) + 3k_5 = 0$$

$$3k_1 + 2k_2 + k_3 + k_4 - k_5 + k_6 = 0$$

$$k_6 = -3k_1 - 2k_2 - k_3 - k_4 + k_5 \qquad (2)$$

$$k_7 = -k_2 + k_5 - (-3k_1 - 2k_2 - k_3 - k_4 + k_5)$$

$$k_7 = 3k_1 + k_2 + k_3 + k_4 \qquad (3)$$

$$k_8 = -3k_1 - 2k_2 - k_4 - (-3k_1 - 2k_2 - k_3 - k_4 + k_5)$$

$$k_8 = k_3 - k_5 \qquad (4)$$

Since there were nine variables (m = 9) and four dimensions (n = 4), five dimensionless groups (m-n = 9-4 = 5) were obtained. The same order of the variables and their corresponding parameters and five dimensionless groups Π_1 to Π_5 were written. From the theory of dimensional analysis, a value of one(1) to k_1 and zero(0) for k_2 to k_5 was assigned. By substituting these values for k_6 to k_9, respective numerical values were obtained. This was repeated for all parameters of the primary variables. The dimensionless groups with corresponding variables is shown below in Table A.2.2. From the Table A.2.2 the dimensionless groups Π_1 to Π_5 were written by equating the product of all the variables raised to respective numerical powers corresponding to them in the row. It can be seen that only one primary variable appears in each dimensionless group which is a unique characteristic of this procedure.

TABLE A.2.2 : Powers of the dimensionless groups

	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
	V	W	T	α	C_p	γ	E	v	K
Π_1	1	0	0	0	0	-3	3	0	0
Π_2	0	1	0	0	0	-2	1	0	0
Π_3	0	0	1	0	0	-1	1	1	0
Π_4	0	0	0	1	0	-1	1	0	0
Π_5	0	0	0	0	1	1	0	-1	-1

The five dimensionless groups are written as

$$\Pi_1 = \frac{VE^3}{\gamma^3}, \quad \Pi_2 = \frac{WE}{\gamma^2}, \quad \Pi_3 = \frac{TEv}{\gamma}, \quad \Pi_4 = \frac{\alpha E}{\gamma}, \quad \Pi_5 = \frac{\gamma C_p}{vK} .$$

From dimensional analysis

$$\Psi \left(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5\right) = 0 ,$$

$$\Psi \left(\frac{VE^3}{\gamma^3}, \frac{WE}{\gamma^2}, \frac{TEv}{\gamma}, \frac{\alpha E}{\gamma}, \frac{\gamma C_p}{vK} \right) = 0 .$$

The dimensionless groups are combined so that each group will have one operating variable and are rewritten as

$$\Psi \left(\frac{VE^3}{\gamma^3}, \frac{WE}{\gamma^2}, \frac{vK}{\gamma C_p}, \frac{TEC_p}{K}, \frac{\alpha E}{\gamma} \right) = 0 .$$

The dependent group with wear volume is expressed in terms of other dimensionless groups with each operating variable as

$$\left(\frac{VE^3}{\gamma^3} \right) = \Psi \left(\frac{WE}{\gamma^2}, \frac{vK}{\gamma C_p}, \frac{TEC_p}{K}, \frac{\alpha E}{\gamma} \right) .$$

This function is written as a mathematical relationship after the undetermined function is evaluated from experimental results which will yield the desired wear equation.

APPENDIX 3

Table A. 3. 1: Material properties and molecular structure of different polymers:

Property---→ [Units]---→ MATERIAL (Molecular structure)	Surface Energy [N/M]	Thermal Conductivity [cals/sec/ $cm^2/{}^\circ C/cm$]	Specific Heat [cals/°C/gm]	Modulus of Elasticity [N/M^2]
Delrin (Poly Oxy Methylene) $-(CH_2\text{-}O\text{-}CH_2\text{-}O)_n-$	0.0312	5.50E-04	0.35	3.11E+09
HDPE High Density Polyethylene $-(CH_2\text{-}CH_2)_n-$	0.0285	5.20E-04	0.55	1.03E+09
PVC Poly Vinyl Chloride $-(CH_2\text{-}CHCl)_n-$	0.0347	2.80E-04	0.24	3.52E+09
Rulon Ceramic filled fluorocarbon $-(CF_2\text{-}CF_2)_n-$	0.0184	7.92E-04	0.24	7.89E+08
Teflon(m)-PTFE Poly Tetra Fluoro Ethylene (Recycled) $-(CF_2\text{-}CF_2)_n-$	0.0180	5.86E-04	0.25	6.52E+08
Teflon(v)-PTFE Virgin PTFE $-(CF_2\text{-}CF_2)_n-$	0.0180	5.86E-04	0.25	6.52E+08

Table A.3.2 (a)

STATISTICAL ANALYSIS OF WEAR VOLUME DATA FOR DELRIN UNDER VARYING LOAD					
MEAN, STD.DEVN, STD. ERROR AND DEV. RATIO OF WEAR VOLUME FOR EACH DATA SET					
LOAD(N)	VOL#1(CU.M)	VOL#2(CU.M)	VOL#3(CU.M)	MEAN	STD.DEV
71.17	4.93E-10	4.93E-10	5.63E-10	5.16E-10	4.07E-11
88.96	6.34E-10	6.34E-10	7.04E-10	6.57E-10	4.07E-11
106.76	8.45E-10	9.15E-10	9.15E-10	8.92E-10	4.07E-11
124.55	1.13E-09	1.27E-09	1.34E-09	1.24E-09	1.08E-10
142.34	1.48E-09	1.55E-09	1.62E-09	1.55E-09	7.04E-11
71.17	4.93E-10	5.63E-10	6.34E-10	5.63E-10	7.04E-11
88.96	8.45E-10	8.45E-10	9.15E-10	8.69E-10	4.07E-11
106.76	8.45E-10	9.86E-10	1.06E-09	9.62E-10	1.08E-10
124.55	1.48E-09	1.69E-09	1.69E-09	1.62E-09	1.22E-10
142.34	1.76E-09	1.83E-09	1.90E-09	1.83E-09	7.04E-11
SDOM	% ERROR(+ or -)	DEV.RATIO(1)	DEV.RATIO(2)	DEV.RATIO(3)	
2.3E-11	4.5	-0.58	-0.58	1.15	
2.3E-11	3.6	-0.58	-0.58	1.15	
2.3E-11	2.6	-1.15	0.58	0.58	
6.2E-11	5.0	-1.09	0.22	0.87	
4.1E-11	2.6	-1.00	0.00	1.00	
4.1E-11	7.2	-1.00	0.00	1.00	
2.3E-11	2.7	-0.58	-0.58	1.15	
6.2E-11	6.5	-1.09	0.22	0.87	
7.0E-11	4.3	-1.15	0.58	0.58	
4.1E-11	2.2	-1.00	0.00	1.00	
FROM CHAUVENET'S CRITERION					
DRo FOR THIS CASE WITH n=3, is 1.38					
IF DR IS GREATER THAN DRo,					
THE DATA POINT IS REJECTED					
NO DATA POINT IS REJECTED					

Table A.3.2 (b)

STATISTICAL ANALYSIS OF WEAR VOLUME DATA FOR DELRIN UNDER VARYING SPEED					
MEAN, STD.DEVN, STD. ERROR AND DEV. RATIO OF WEAR VOLUME FOR EACH DATA SET					
SPEED (M/S)	VOL#1(CU.M)	VOL#2(CU.M)	VOL#3(CU.M)	MEAN	STD.DEV
0.125	7.04E-11	7.04E-11	7.04E-11	7.04E-11	0.00E+00
0.250	2.82E-10	2.82E-10	3.52E-10	3.05E-10	4.07E-11
0.375	4.23E-10	4.93E-10	5.63E-10	4.93E-10	7.04E-11
0.500	6.34E-10	6.34E-10	7.04E-10	6.57E-10	4.07E-11
0.625	1.27E-09	1.41E-09	1.55E-09	1.41E-09	1.41E-10
0.125	7.04E-11	7.04E-11	7.04E-11	7.04E-11	0.00E+00
0.250	2.11E-10	2.11E-10	2.82E-10	2.35E-10	4.07E-11
0.375	4.23E-10	4.93E-10	5.63E-10	4.93E-10	7.04E-11
0.500	7.04E-10	8.45E-10	9.15E-10	8.22E-10	1.08E-10
0.625	9.86E-10	9.86E-10	1.06E-09	1.01E-09	4.06E-11
SDOM	% ERROR(+ or -)	DEV.RATIO(1)	DEV.RATIO(2)	DEV.RATIO(3)	
0.0E+00	0.0	0.00	0.00	0.00	
2.3E-11	7.7	-0.58	-0.58	1.15	
4.1E-11	8.2	-1.00	0.00	1.00	
2.3E-11	3.6	-0.58	-0.58	1.15	
8.1E-11	5.8	-1.00	0.00	1.00	
0.0E+00	0.0	0.00	0.00	0.00	
2.3E-11	10.0	-0.58	-0.58	1.15	
4.1E-11	8.2	-1.00	0.00	1.00	
6.2E-11	7.6	-1.09	0.22	0.87	
2.3E-11	2.3	-0.58	-0.58	1.15	
FROM CHAUVENET'S CRITERION					
DRo FOR THIS CASE WITH n=3, is 1.38					
IF DR IS GREATER THAN DRo,					
THE DATA POINT IS REJECTED					
NO DATA POINT IS REJECTED					

Table A.3.2 (c)

STATISTICAL ANALYSIS OF WEAR VOLUME DATA FOR DELRIN UNDER VARYING DURATION					
MEAN, STD.DEVN, STD. ERROR AND DEV. RATIO OF WEAR VOLUME FOR EACH DATA SET					
TIME (SECS)	VOL#1(CU.M)	VOL#2(CU.M)	VOL#3(CU.M)	MEAN	STD.DEV
18000	5.63E-10	5.63E-10	6.34E-10	5.87E-10	4.07E-11
36000	1.27E-09	1.34E-09	1.34E-09	1.31E-09	4.06E-11
54000	1.62E-09	1.76E-09	1.83E-09	1.74E-09	1.08E-10
72000	2.61E-09	2.75E-09	2.82E-09	2.72E-09	1.08E-10
90000	4.51E-09	4.58E-09	4.65E-09	4.58E-09	7.05E-11
18000	7.75E-10	8.45E-10	9.15E-10	8.45E-10	7.04E-11
36000	1.62E-09	1.76E-09	1.83E-09	1.74E-09	1.08E-10
54000	2.25E-09	2.39E-09	2.39E-09	2.35E-09	8.13E-11
72000	2.68E-09	2.89E-09	2.89E-09	2.82E-09	1.22E-10
90000	3.31E-09	3.38E-09	3.52E-09	3.40E-09	1.08E-10
SDOM	% ERROR(+ or -)	DEV.RATIO(1)	DEV.RATIO(2)	DEV.RATIO(3)	
2.3E-11	4.0	-0.58	-0.58	1.15	
2.3E-11	1.8	-1.15	0.58	0.58	
6.2E-11	3.6	-1.09	0.22	0.87	
6.2E-11	2.3	-1.09	0.22	0.87	
4.1E-11	0.9	-1.00	0.00	1.00	
4.1E-11	4.8	-1.00	0.00	1.00	
6.2E-11	3.6	-1.09	0.22	0.87	
4.7E-11	2.0	-1.15	0.58	0.58	
7.0E-11	2.5	-1.15	0.58	0.58	
6.2E-11	1.8	-0.87	-0.22	1.09	
FROM CHAUVENET'S CRITERION					
DRo FOR THIS CASE WITH n=3, is 1.38					
IF DR IS GREATER THAN DRo,					
THE DATA POINT IS REJECTED					
NO DATA POINT IS REJECTED					

Table A.3.2 (d)

STATISTICAL ANALYSIS OF WEAR VOLUME DATA FOR DELRIN UNDER VARYING ROUGHNES					
MEAN, STD.DEVN, STD. ERROR AND DEV. RATIO OF WEAR VOLUME FOR EACH DATA SET					
ROUGH(MIC)	ROUGH(MIC)	ROUGH(MIC)	VOL#1(CU.M)	VOL#2(CU.M)	VOL#3(CU.M)
0.0875	0.1000	0.1100	4.23E-10	4.93E-10	5.63E-10
0.1520	0.1640	0.1740	5.63E-10	6.34E-10	6.34E-10
0.2100	0.2250	0.2380	9.15E-10	1.06E-09	1.13E-09
0.2540	0.2650	0.2680	1.13E-09	1.13E-09	1.20E-09
0.3380	0.3460	0.3670	1.69E-09	1.76E-09	1.97E-09
0.0440	0.0500	0.0620	2.82E-10	3.52E-10	4.23E-10
0.0997	0.1020	0.1120	6.34E-10	6.34E-10	7.75E-10
0.1658	0.1720	0.1780	7.04E-10	9.15E-10	9.86E-10
0.2160	0.2250	0.2370	8.45E-10	9.86E-10	1.13E-09
0.2860	0.3000	0.3210	1.13E-09	1.20E-09	1.27E-09
0.3360	0.3450	0.3650	1.55E-09	1.62E-09	1.76E-09
	MEAN	STD.DEV	SDOM	% ERROR(+ or -)	
	4.93E-10	7.04E-11	4.1E-11	8.2	
	6.10E-10	4.07E-11	2.3E-11	3.8	
	1.03E-09	1.08E-10	6.2E-11	6.0	
	1.15E-09	4.06E-11	2.3E-11	2.0	
	1.81E-09	1.47E-10	8.5E-11	4.7	
	3.52E-10	7.04E-11	4.1E-11	11.5	
	6.81E-10	8.13E-11	4.7E-11	6.9	
	8.69E-10	1.47E-10	8.5E-11	9.7	
	9.86E-10	1.41E-10	8.1E-11	8.2	
	1.20E-09	7.04E-11	4.1E-11	3.4	
	1.64E-09	1.08E-10	6.2E-11	3.8	
DEV.RATIO(1)	DEV.RATIO(2)	DEV.RATIO(3)	FROM CHAUVENET'S CRITERION		
-1.00	0.00	1.00	DRo FOR THIS CASE WITH n=3, is 1.38		
-1.15	0.58	0.58	IF DR IS GREATER THAN DRo,		
-1.09	0.22	0.87	THE DATA POINT IS REJECTED		
-0.58	-0.58	1.15	**NO DATA POINT IS REJECTED**		
-0.80	-0.32	1.12			
-1.00	0.00	1.00			
-0.58	-0.58	1.15			
-1.12	0.32	0.80			
-1.00	0.00	1.00			
-1.00	0.00	1.00			
-0.87	-0.22	1.09			

Table A.3.2 (e)

STATISTICAL ANALYSIS OF THE EXPONENTS WITH DIFFERENT VARIABLES FOR DELRIN					
MEAN, STD.DEVN, STD. ERROR AND DEV. RATIO OF SLOPES FOR EACH DATA SET					
VARIABLE	EXPONENT #1	EXPONENT #2	EXPONENT #3	MEAN EXPONENT	STD.DEV
LOAD	1.693	1.742	1.697	1.711	0.027
SLIDING SPEED	1.673	1.725	1.735	1.711	0.033
SLIDING TIME	1.042	1.030	0.999	1.024	0.022
ROUGHNESS	0.738	0.737	0.710	0.728	0.016
SDOM	% ERROR(+ or -)	DEV.RATIO(1)	DEV.RATIO(2)	DEV.RATIO(3)	
1.6E-02	0.9	-0.65	1.15	-0.50	
1.9E-02	1.1	-1.14	0.42	0.72	
1.3E-02	1.3	0.83	0.29	-1.11	
9.2E-03	1.3	0.61	0.55	-1.15	
FROM CHAUVENET'S CRITERION					
DRo FOR THIS CASE WITH n=3, is 1.38					
IF DR IS GREATER THAN DRo,					
THE DATA POINT IS REJECTED					
NO DATA POINT IS REJECTED					

Table A.3.2 (f)

MEAN, STD.DEVN, STD. ERROR AND DEV. RATIO OF INDIVIDUAL WEAR COEFFITS FOR DELRIN					
INDIVIDUAL kw	DEV.RATIO		WITH LINEAR MODEL		
1.62E-10	-0.30				
1.92E-10	0.30				
1.77E-10	0.01				
2.56E-10	1.62				
2.62E-10	1.74				
1.47E-10	-0.61				
1.52E-10	-0.51				
1.74E-10	-0.06				
2.21E-10	0.89				
2.40E-10	1.28				
1.92E-10	0.30				
2.03E-10	0.53		FROM CHAUVENET'S CRITERION		
1.88E-10	0.23		DRo FOR THIS CASE WITH n=44, is 2.57		
1.62E-10	-0.31		IF DR IS GREATER THAN DRo,		
1.50E-10	-0.56		THE DATA POINT IS REJECTED		
1.40E-10	-0.75		**ONE DATA POINT IS REJECTED**		
1.59E-10	-0.37				
1.35E-10	-0.85				
1.54E-10	-0.47		AVERAGE =	1.74E-10	
2.06E-10	0.60				
6.35E-11	-2.31		STD.DEV =	4.51E-11	
1.30E-10	-0.95				
1.53E-10	-0.49		S D O M =	6.88E-12	
1.52E-10	-0.51				
2.61E-10	1.70		% ERROR =	4.0	
5.69E-11	-2.44				
1.02E-10	-1.53	**FINAL WEAR**			
1.46E-10	-0.62	**COEFFICIENT ' kw '=**		1.74E-10 ± 4%	
1.92E-10	0.30				
1.91E-10	0.28				
2.75E-10	2.00				
1.92E-10	0.30				
1.71E-10	-0.12				
1.74E-10	-0.05				
1.49E-10	-0.56				
1.83E-10	0.12				
1.78E-10	0.01				
1.52E-10	-0.51				
1.51E-10	-0.53				
1.89E-10	0.23				
1.73E-10	-0.08				
1.68E-10	-0.19				
2.04E-10	0.56				
3.12E-10	**2.74**	***REJECTED**			

Table A.3.2 (g)

MEAN, STD.DEVN, STD. ERROR AND DEV. RATIO OF INDIVIDUAL WEAR COEFFITS FOR DELRIN					
INDIVIDUAL kw	DEV.RATIO		WITH EXPONENTIAL MODEL		
3.79E-18	0.38				
3.84E-18	0.47				
3.13E-18	-0.84				
4.07E-18	0.90				
3.75E-18	0.31				
3.41E-18	-0.33				
3.00E-18	-1.09				
3.03E-18	-1.04				
3.39E-18	-0.37				
3.36E-18	-0.42				
4.31E-18	1.35				
4.75E-18	2.17		FROM CHAUVENET'S CRITERION		
3.84E-18	0.47		DRo FOR THIS CASE WITH n=44, is 2.57		
3.65E-18	0.12		IF DR IS GREATER THAN DRo,		
3.81E-18	0.42		THE DATA POINT IS REJECTED		
3.49E-18	-0.18		**NO DATA POINT IS REJECTED**		
4.44E-18	1.58				
3.14E-18	-0.83				
3.00E-18	-1.09		AVERAGE =	3.59E-18	
3.07E-18	-0.95				
4.01E-18	0.79		STD.DEV =	5.39E-19	
3.79E-18	0.38				
3.77E-18	0.35		S D O M =	8.13E-20	
4.97E-18	2.56				
3.42E-18	-0.32		% ERROR =	2.3	
4.34E-18	1.39				
3.74E-18	0.28	**FINAL WEAR**			
3.00E-18	-1.09	**COEFFICIENT ' kw ' =**		3.59E – 18 ± 2.3 %	
4.43E-18	1.57				
3.15E-18	-0.81				
3.37E-18	-0.41				
3.62E-18	0.05				
3.84E-18	0.47				
3.21E-18	-0.71				
3.84E-18	0.47				
3.99E-18	0.74				
3.61E-18	0.04				
3.13E-18	-0.85				
2.90E-18	-1.27				
2.77E-18	-1.52				
3.07E-18	-0.97				
2.62E-18	-1.80				
2.98E-18	-1.13				
3.99E-18	0.74				

TABLE A.3.3. : Wear volume and Coefficient of friction of DELRIN sliding against AISI 1018 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 18000 s, Roughness = 0.1604 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00070	4.93E-10	0.5112	0.437-0.557
88.96	0.00090	6.34E-10	0.5786	0.450-0.681
106.76	0.00125	8.80E-10	0.5611	0.454-0.639
124.55	0.00175	1.23E-09	0.5701	0.482-0.615
142.34	0.00220	1.55E-09	0.5527	0.459-0.613
Variable : SPEED				
(Load = 88.96 N, Time = 18000 s, Roughness = 0.1705 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00010	7.04E-11	0.4988	0.437-0.528
0.250	0.00043	3.03E-10	0.5057	0.445-0.539
0.375	0.00070	4.93E-10	0.5153	0.461-0.563
0.500	0.00090	6.34E-10	0.5786	0.450-0.681
0.625	0.00200	1.41E-09	0.5863	0.475-0.683
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.1666 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00083	5.85E-10	0.5786	0.450-0.681
36000	0.00185	1.30E-09	0.5706	0.430-0.634
54000	0.00245	1.73E-09	0.5815	0.430-0.645
72000	0.00385	2.71E-09	0.5709	0.451-0.628
90000	0.00650	4.58E-09	0.5604	0.551-0.572
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 18000 s)				
ROUGHNESS(mic)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.1081	0.00070	4.93E-10	0.4918	0.452-0.542
0.1626	0.00090	6.34E-10	0.5786	0.450-0.681
0.1815	0.00100	7.04E-10	0.5326	0.430-0.553
0.2150	0.00147	1.04E-09	0.4664	0.400-0.525
0.2386	0.00150	1.06E-09	0.4581	0.374-0.477
0.2623	0.00160	1.13E-09	0.4275	0.418-0.450
0.3489	0.00260	1.83E-09	0.4016	0.375-0.426

TABLE A.3.4. : Wear volume and Coefficient of friction of DELRIN sliding against HTSR 4140 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s. Time = 18000 s. Roughness = 0.1721 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00080	5.63E-10	0.5054	0.370-0.580
88.96	0.00120	8.45E-10	0.4899	0.414-0.521
106.76	0.00135	9.51E-10	0.4899	0.434-0.529
124.55	0.00230	1.62E-09	0.4991	0.431-0.568
142.34	0.00260	1.83E-09	0.5064	0.488-0.532
Variable : SPEED				
(Load = 88.96 N. Time = 18000 s. Roughness = 0.1758 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00010	7.04E-11	0.4479	0.395-0.480
0.250	0.00033	2.32E-10	0.4518	0.367-0.488
0.375	0.00070	4.93E-10	0.4627	0.425-0.481
0.500	0.00120	8.45E-10	0.4899	0.414-0.521
0.625	0.00140	9.86E-10	0.5168	0.408-0.600
Variable : TIME				
(Load = 88.96 N. Speed = 0.5 m/s. Roughness = 0.1693 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00120	8.45E-10	0.4899	0.414-0.521
36000	0.00250	1.76E-09	0.5057	0.495-0.621
54000	0.00330	2.32E-09	0.5270	0.447-0.635
72000	0.00400	2.82E-09	0.5207	0.461-0.570
90000	0.00480	3.38E-09	0.5438	0.473-0.657
Variable : ROUGHNESS				
(Load = 88.96 N. Speed = 0.5 m/s. Time = 18000 s)				
ROUGHNESS(mic	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0440	0.00050	3.52E-10	0.5163	0.492-0.533
0.0997	0.00100	7.04E-10	0.5443	0.467-0.646
0.1719	0.00120	8.45E-10	0.4899	0.414-0.521
0.2165	0.00135	9.51E-10	0.4789	0.400-0.534
0.2368	0.00150	1.06E-09	0.4360	0.388-0.477
0.3028	0.00165	1.16E-09	0.4130	0.379-0.460
0.3470	0.00232	1.63E-09	0.4115	0.408-0.415

TABLE A.3.5. : Wear volume and Coefficient of friction of HDPE sliding against AISI 1018 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 18000 s, Roughness = 0.1263 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00187	1.96E-09	0.2996	0.267-0.321
88.96	0.00260	2.73E-09	0.3264	0.276-0.354
106.76	0.00360	3.78E-09	0.3276	0.269-0.400
124.55	0.00470	4.93E-09	0.3361	0.297-0.399
142.34	0.00560	5.88E-09	0.3423	0.306-0.409
Variable : SPEED				
(Load = 88.96 N, Time = 18000 s, Roughness = 0.1263 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00015	1.57E-10	0.2141	0.193-0.256
0.250	0.00030	3.15E-10	0.2508	0.213-0.284
0.375	0.00120	1.26E-09	0.2654	0.245-0.289
0.500	0.00260	2.73E-09	0.3264	0.276-0.354
0.625	0.00555	5.83E-09	0.4714	0.389-0.503
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.1247 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00260	2.73E-09	0.3264	0.267-0.321
36000	0.00475	4.99E-09	0.2921	0.233-0.347
54000	0.00840	8.82E-09	0.3071	0.262-0.364
72000	0.01345	1.41E-08	0.3131	0.257-0.359
90000	0.02290	2.40E-08	0.3497	0.268-0.435
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 18000 s)				
ROUGHNESS(mic)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0649	0.00050	5.25E-10	0.2939	0.285-0.303
0.0786	0.00080	8.40E-10	0.2862	0.271-0.303
0.1350	0.00260	2.73E-09	0.3264	0.276-0.354
0.1595	0.00450	4.72E-09	0.3661	0.314-0.399
0.2281	0.00540	5.67E-09	0.3396	0.333-0.358
0.3624	0.00640	6.72E-09	0.2887	0.286-0.293

TABLE A.3.6. : Wear volume and Coefficient of friction of HDPE sliding against HTSR 4140 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 18000 s, Roughness = 0.1260 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00250	2.62E-09	0.2924	0.273-0.306
88.96	0.00315	3.31E-09	0.3275	0.273-0.356
106.76	0.00375	3.94E-09	0.3211	0.307-0.334
124.55	0.00470	4.93E-09	0.3487	0.323-0.381
142.34	0.00535	5.62E-09	0.3556	0.295-0.411
Variable : SPEED				
(Load = 88.96 N, Time = 18000 s, Roughness = 0.1246 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00010	1.05E-10	0.2066	0.182-0.241
0.250	0.00030	3.15E-10	0.2703	0.247-0.287
0.375	0.00150	1.57E-09	0.2816	0.264-0.291
0.500	0.00315	3.31E-09	0.3275	0.273-0.356
0.625	0.00520	5.46E-09	0.4356	0.366-0.462
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.1238 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00315	3.31E-09	0.3275	0.273-0.356
36000	0.00830	8.71E-09	0.3636	0.308-0.396
54000	0.01120	1.18E-08	0.3372	0.290-0.399
72000	0.01405	1.48E-08	0.3477	0.312-0.436
90000	0.02230	2.34E-08	0.3691	0.307-0.444
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 18000 s)				
ROUGHNESS(mic	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0591	0.00050	5.25E-10	0.2755	0.216-0.289
0.0968	0.00210	2.20E-09	0.3054	0.264-0.356
0.1259	0.00315	3.31E-09	0.3275	0.273-0.356
0.1832	0.00360	3.78E-09	0.2921	0.263-0.320
0.2208	0.00430	4.51E-09	0.2955	0.263-0.377
0.2584	0.00640	6.72E-09	0.3182	0.273-0.342
0.3750	0.00770	8.08E-09	0.2866	0.273-0.296

TABLE A.3.7. : Wear volume and Coefficient of friction of PVC sliding against AISI 1018 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 18000 s, Roughness = 0.1503 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00075	5.17E-10	0.3971	0.301-0.437
88.96	0.00103	7.10E-10	0.3859	0.314-0.445
106.76	0.00135	9.31E-10	0.3753	0.312-0.413
124.55	0.00213	1.47E-09	0.3841	0.280-0.483
142.34	0.00400	2.76E-09	0.3278	0.303-0.346
Variable : SPEED				
(Load = 88.96 N, Time = 18000 s, Roughness = 0.1127 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00025	1.72E-10	0.4014	0.367-0.449
0.250	0.00035	2.41E-10	0.4069	0.310-0.464
0.375	0.00055	3.79E-10	0.3729	0.325-0.412
0.500	0.00085	5.86E-10	0.3737	0.312-0.446
0.625	0.00145	1.00E-09	0.3942	0.315-0.436
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.1531 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00103	7.10E-10	0.3859	0.314-0.445
36000	0.00190	1.31E-09	0.3578	0.317-0.426
54000	0.00215	1.48E-09	0.3564	0.329-0.383
72000	0.00240	1.66E-09	0.3675	0.311-0.420
90000	0.00320	2.21E-09	0.3474	0.295-0.421
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 18000 s)				
ROUGHNESS(mic	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0635	0.00100	6.90E-10	0.3937	0.356-0.448
0.1171	0.00085	5.86E-10	0.3737	0.312-0.446
0.1526	0.00103	7.10E-10	0.3859	0.314-0.445
0.1907	0.00110	7.59E-10	0.3582	0.312-0.446
0.2277	0.00125	8.62E-10	0.3367	0.317-0.388
0.3184	0.00180	1.24E-09	0.3252	0.298-0.359
0.3439	0.00260	1.7931E-09	0.2513	0.242-0.260

TABLE A.3.8. : Wear volume and Coefficient of friction of PVC sliding against HTSR 4140 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 18000 s, Roughness = 0.1419 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00085	5.86E-10	0.4216	0.388-0.456
88.96	0.00100	6.90E-10	0.3925	0.367-0.450
106.76	0.00140	9.66E-10	0.3888	0.366-0.443
124.55	0.00240	1.66E-09	0.3640	0.330-0.388
142.34	0.00270	1.86E-09	0.3610	0.332-0.391
Variable : SPEED				
(Load = 88.96 N, Time = 18000 s, Roughness = 0.1137 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00020	1.38E-10	0.4509	0.417-0.464
0.250	0.00030	2.07E-10	0.4646	0.440-0.495
0.375	0.00050	3.45E-10	0.4587	0.403-0.495
0.500	0.00080	5.52E-10	0.4286	0.379-0.478
0.625	0.00175	1.21E-09	0.4233	0.369-0.455
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.1463 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00100	6.90E-10	0.3925	0.367-0.450
36000	0.00170	1.17E-09	0.3505	0.330-0.378
54000	0.00220	1.52E-09	0.3800	0.353-0.443
72000	0.00260	1.79E-09	0.3693	0.306-0.475
90000	0.00325	2.24E-09	0.3789	0.305-0.458
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 18000 s)				
ROUGHNESS(mic)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0519	0.00130	8.97E-10	0.4403	0.361-0.541
0.1171	0.00080	5.52E-10	0.4286	0.379-0.478
0.1449	0.00100	6.90E-10	0.3925	0.367-0.456
0.1678	0.00110	7.59E-10	0.3456	0.300-0.382
0.2102	0.00147	1.01E-09	0.3386	0.305-0.392
0.2919	0.00200	1.38E-09	0.3092	0.304-0.316
0.3694	0.00240	1.66E-09	0.2836	0.275-0.297

TABLE A.3.9. : Wear volume and Coefficient of friction of RULON sliding against AISI 1018 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 18000 s, Roughness = 0.1303 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00070	3.10E-10	0.2257	0.216-0.235
88.96	0.00090	3.98E-10	0.2298	0.211-0.257
106.76	0.00100	4.42E-10	0.2162	0.199-0.225
124.55	0.00120	5.31E-10	0.2417	0.212-0.262
142.34	0.00170	7.52E-10	0.2384	0.228-0.252
Variable : SPEED				
(Load = 88.96 N, Time = 18000 s, Roughness = 0.1284 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00045	1.99E-10	0.2217	0.210-0.230
0.250	0.00063	2.79E-10	0.2274	0.211-0.243
0.375	0.00080	3.54E-10	0.2282	0.216-0.239
0.500	0.00090	3.98E-10	0.2298	0.211-0.257
0.625	0.00155	6.86E-10	0.2278	0.209-0.234
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.1277 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00090	3.98E-10	0.2298	0.211-0.257
36000	0.00170	7.52E-10	0.2142	0.205-0.221
54000	0.00210	9.29E-10	0.2146	0.211-0.218
72000	0.00260	1.15E-09	0.2167	0.206-0.221
90000	0.00315	1.39E-09	0.2211	0.206-0.227
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 18000 s)				
ROUGHNESS(mic)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0864	0.00075	3.32E-10	0.2727	0.259-0.280
0.1458	0.00090	3.98E-10	0.2298	0.211-0.257
0.1976	0.00095	4.20E-10	0.2133	0.183-0.233
0.2513	0.00105	4.65E-10	0.2124	0.227-0.264
0.2868	0.00120	5.31E-10	0.2101	0.200-0.216
0.3070	0.00130	5.75E-10	0.2077	0.205-0.215
0.3680	0.00160	7.08E-10	0.1896	0.183-0.198

TABLE A.3.10. : Wear volume and Coefficient of friction of RULON sliding against HTSR 4140 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 18000 s, Roughness = 0.1302 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.00055	2.43E-10	0.2194	0.198-0.232
88.96	0.00075	3.32E-10	0.2340	0.205-0.252
106.76	0.00107	4.73E-10	0.2248	0.201-0.246
124.55	0.00140	6.19E-10	0.2196	0.191-0.235
142.34	0.00160	7.08E-10	0.2235	0.201-0.241
Variable : SPEED				
(Load = 88.96 N, Time = 18000 s, Roughness = 0.1273 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.00040	1.77E-10	0.1893	0.156-0.215
0.250	0.00060	2.65E-10	0.2165	0.210-0.243
0.375	0.00070	3.10E-10	0.2258	0.215-0.241
0.500	0.00080	3.54E-10	0.2340	0.205-0.252
0.625	0.00125	5.53E-10	0.2147	0.202-0.223
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.1301 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
18000	0.00080	3.54E-10	0.2340	0.205-0.252
36000	0.00160	7.08E-10	0.2225	0.212-0.236
54000	0.00200	8.85E-10	0.2193	0.204-0.232
72000	0.00240	1.06E-09	0.2171	0.197-0.230
90000	0.00275	1.22E-09	0.2176	0.189-0.233
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 18000 s)				
ROUGHNESS(mic	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.1043	0.00060	2.65E-10	0.2309	0.229-0.240
0.1324	0.00075	3.32E-10	0.2340	0.205-0.252
0.1675	0.00080	3.54E-10	0.2386	0.236-0.252
0.2049	0.00090	3.98E-10	0.2199	0.186-0.239
0.2398	0.00095	4.20E-10	0.2127	0.186-0.234
0.2834	0.00110	4.87E-10	0.1801	0.157-0.194
0.3327	0.00140	6.19E-10	0.1734	0.136-0.192

TABLE A.3.11. : Wear volume and Coefficient of friction of TEFLON(M) sliding against AISI 1018 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 6000 s, Roughness = 0.0484 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.1629	7.27E-08	0.2591	0.250-0.265
88.96	0.2171	9.69E-08	0.2614	0.256-0.268
106.76	0.2661	1.19E-07	0.2592	0.256-0.266
124.55	0.3495	1.56E-07	0.2598	0.255-0.269
142.34	0.4693	2.10E-07	0.2575	0.244-0.265
Variable : SPEED				
(Load = 88.96 N, Time = 6000 s, Roughness = 0.1160 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.0969	4.33E-08	0.1988	0.190-0.204
0.250	0.1631	7.28E-08	0.2202	0.213-0.230
0.375	0.2031	9.07E-08	0.2225	0.206-0.239
0.500	0.2491	1.11E-07	0.2324	0.213-0.248
0.625	0.3029	1.35E-07	0.2461	0.221-0.265
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.0499 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
3000	0.1237	5.52E-08	0.2621	0.258-0.266
4500	0.1706	7.62E-08	0.2591	0.251-0.269
6000	0.2171	9.69E-08	0.2614	0.256-0.268
7500	0.2572	1.15E-07	0.2648	0.261-0.270
9000	0.2886	1.29E-07	0.2571	0.231-0.262
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 6000 s)				
ROUGHNESS(mic	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0500	0.2171	9.69E-08	0.2614	0.256-0.268
0.0993	0.2491	1.11E-07	0.2324	0.213-0.248
0.1526	0.2747	1.23E-07	0.2297	0.204-0.251
0.1832	0.2865	1.28E-07	0.2248	0.208-0.251
0.2052	0.3052	1.36E-07	0.2201	0.208-0.234
0.2203	0.3228	1.44E-07	0.2108	0.207-0.229

TABLE A.3.12. : Wear volume and Coefficient of friction of TEFLON(M) sliding against HTSR 4140 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 6000 s, Roughness = 0.0451 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.1608	7.18E-08	0.2642	0.261-0.269
88.96	0.2176	9.71E-08	0.2618	0.250-0.268
106.76	0.2984	1.33E-07	0.2620	0.260-0.268
124.55	0.3747	1.67E-07	0.2592	0.254-0.263
142.34	0.4487	2.00E-07	0.2557	0.250-0.259
Variable : SPEED				
(Load = 88.96 N, Time = 6000 s, Roughness = 0.1198 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.0944	4.21E-08	0.2064	0.202-0.213
0.250	0.1609	7.18E-08	0.2240	0.216-0.228
0.375	0.2188	9.77E-08	0.2355	0.212-0.246
0.500	0.2587	1.15E-07	0.2536	0.238-0.261
0.625	0.2845	1.27E-07	0.2586	0.248-0.269
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.0462 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
3000	0.1294	5.78E-08	0.2596	0.245-0.264
4500	0.1621	7.24E-08	0.2631	0.258-0.268
6000	0.2176	9.71E-08	0.2618	0.250-0.268
7500	0.2498	1.12E-07	0.2571	0.231-0.262
9000	0.2965	1.32E-07	0.2564	0.239-0.260
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 6000 s)				
ROUGHNESS(mic	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0432	0.2176	9.71E-08	0.2618	0.250-0.268
0.0730	0.2385	1.06E-07	0.2559	0.236-0.259
0.1126	0.2587	1.15E-07	0.2536	0.238-0.261
0.1472	0.2894	1.29E-07	0.2504	0.218-0.258
0.1739	0.3026	1.35E-07	0.2405	0.218-0.249
0.1947	0.3220	1.44E-07	0.2370	0.208-0.244
0.2294	0.3407	1.52E-07	0.2305	0.207-0.243

TABLE A.3.13. : Wear volume and Coefficient of friction of TEFLON(V) sliding against AISI 1018 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 6000 s, Roughness = 0.0477 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.1651	7.61E-08	0.2984	0.291-0.305
88.96	0.2018	9.30E-08	0.2922	0.280-0.297
106.76	0.2491	1.15E-07	0.2934	0.286-0.308
124.55	0.3508	1.62E-07	0.2863	0.277-0.308
142.34	0.3851	1.77E-07	0.2876	0.279-0.288
Variable : SPEED				
(Load = 88.96 N, Time = 6000 s, Roughness = 0.1111 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.0927	4.27E-08	0.2276	0.223-0.231
0.250	0.1345	6.20E-08	0.2521	0.236-0.263
0.375	0.2371	1.09E-07	0.2594	0.265-0.275
0.500	0.3121	1.44E-07	0.2802	0.276-0.285
0.625	0.3625	1.67E-07	0.2827	0.273-0.286
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.0480 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
3000	0.1245	5.74E-08	0.2943	0.289-0.300
4500	0.1572	7.24E-08	0.2964	0.292-0.309
6000	0.2018	9.30E-08	0.2922	0.280-0.297
7500	0.2352	1.08E-07	0.2956	0.287-0.300
9000	0.2655	1.22E-07	0.2941	0.287-0.301
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 6000 s)				
ROUGHNESS(mic)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0470	0.2018	9.30E-08	0.2922	0.280-0.297
0.0861	0.3051	1.41E-07	0.2874	0.275-0.289
0.1190	0.3121	1.44E-07	0.2802	0.276-0.285
0.1369	0.3465	1.60E-07	0.2744	0.259-0.280
0.1664	0.3946	1.82E-07	0.2598	0.249-0.269
0.2144	0.4434	2.04E-07	0.2516	0.228-0.262

TABLE A.3.14. : Wear volume and Coefficient of friction of TEFLON(V) sliding against HTSR 4140 steel under different operating variables

Variable : LOAD				
(Speed = 0.5 m/s, Time = 6000 s, Roughness = 0.0473 microns)				
LOAD (N)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
71.17	0.1112	5.12E-08	0.2948	0.287 - 0.305
88.96	0.1571	7.24E-08	0.2950	0.287 - 0.307
106.76	0.1934	8.91E-08	0.2891	0.280 - 0.303
124.55	0.2278	1.05E-07	0.2816	0.280 - 0.301
142.34	0.2767	1.28E-07	0.2810	0.277 - 0.293
Variable : SPEED				
(Load = 88.96 N, Time = 6000 s, Roughness = 0.1303 microns)				
SPEED (m/s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.125	0.0876	4.04E-08	0.2238	0.218 - 0.227
0.250	0.1270	5.85E-08	0.2541	0.248 - 0.257
0.375	0.2114	9.74E-08	0.2726	0.262 - 0.285
0.500	0.2486	1.15E-07	0.2742	0.250 - 0.279
0.625	0.3053	1.41E-07	0.2785	0.265 - 0.295
Variable : TIME				
(Load = 88.96 N, Speed = 0.5 m/s, Roughness = 0.0463 microns)				
TIME (s)	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
3000	0.0924	4.26E-08	0.2848	0.280 - 0.292
4500	0.1257	5.79E-08	0.2864	0.281 - 0.292
6000	0.1571	7.24E-08	0.2950	0.287 - 0.307
7500	0.1733	7.99E-08	0.2885	0.279 - 0.294
9000	0.1884	8.68E-08	0.2916	0.282 - 0.305
Variable : ROUGHNESS				
(Load = 88.96 N, Speed = 0.5 m/s, Time = 6000 s)				
ROUGHNESS(mic	Wt. loss (gms)	Vol. loss (cu.m)	Coef. of friction	Range of c.o.f.
0.0495	0.1571	7.24E-08	0.2950	0.287 - 0.307
0.1046	0.2486	1.15E-07	0.2742	0.250 - 0.279
0.1375	0.3383	1.56E-07	0.2598	0.254 - 0.265
0.1586	0.3590	1.65E-07	0.2698	0.267 - 0.276
0.1794	0.4225	1.95E-07	0.2512	0.249 - 0.253
0.2022	0.4456	2.05E-07	0.2442	0.227 - 0.257
0.2455	0.4596	2.12E-07	0.2337	0.216 - 0.254

TABLE A.3.15. : Wear volume and Coefficient of friction of different polymers sliding against AISI 1018 steel and HTSR 4140 steel at different sliding speeds

	MILD STEEL		HTSR 4140 STEEL	
at 0.125 m/s				
MATERIAL	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
Delrin	7.04E-11	0.4988	7.04E-11	0.4479
HDPE	1.58E-10	0.2141	1.05E-10	0.2066
PVC	1.72E-10	0.4014	1.38E-10	0.4509
Rulon	1.99E-10	0.2217	1.77E-10	0.1893
LDPE	6.51E-09	0.6162	3.36E-09	0.5791
Polypropylene	9.59E-09	0.6137	7.27E-09	0.6185
at 0.25 m/s				
MATERIAL	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
PVC	2.41E-10	0.4069	2.07E-10	0.4646
Delrin	3.03E-10	0.5057	2.32E-10	0.4518
Rulon	2.79E-10	0.2274	2.66E-10	0.2165
HDPE	3.15E-10	0.2508	3.15E-10	0.2703
Nylon	7.83E-10	0.4486	4.35E-10	0.4949
Nylatron GS	1.21E-09	0.5828	1.21E-09	0.6016
LDPE	1.45E-08	0.6145	1.63E-08	0.6248
at 0.5 m/s				
MATERIAL	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
UHMWPE	1.06E-10	0.2187	1.06E-10	0.2222
Foulton	2.40E-10	0.3064	2.60E-10	0.3256
Rulon	3.98E-10	0.2298	3.54E-10	0.2386
PVC	7.59E-10	0.3582	7.59E-10	0.3456
Delrin	7.04E-10	0.5326	8.45E-10	0.4899
Nylon	3.10E-09	0.4915	3.04E-09	0.4088
Nylatron GS	3.92E-09	0.5747	3.36E-09	0.5068
HDPE	4.72E-09	0.3661	3.78E-09	0.2921

Test Conditions: Load: 88.96 N; Time: 18000 sec; Counterface Roughness: 0.15 microns

TABLE A.3.16. : Comparison of wear volume and coefficient of friction of different polymers sliding against AISI 1018 steel and HTSR 4140 steel at different operating variables

	MILD STEEL		HTSR 4140 STEEL	
NYLON				
LOAD (N)	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
36	1.04E-09	0.4931	6.70E-10	0.4168
54	1.39E-09	0.5268	1.16E-09	0.4127
90	3.10E-09	0.4915	3.04E-09	0.4088
TEFLON (V)				
SPEED (m/s)	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
0.125	4.27E-08	0.2276	4.04E-08	0.2238
0.250	6.20E-08	0.2521	5.85E-08	0.2541
0.375	1.09E-07	0.2594	9.74E-08	0.2726
0.500	1.44E-07	0.2802	1.15E-07	0.2742
0.625	1.67E-07	0.2827	1.41E-07	0.2785
HDPE				
TIME (sec)	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
18000	2.73E-09	0.3264	3.31E-09	0.3275
36000	4.99E-09	0.2921	8.71E-09	0.3636
54000	8.82E-09	0.3071	1.18E-08	0.3372
72000	1.41E-08	0.3131	1.48E-08	0.3477
90000	2.40E-08	0.3497	2.34E-08	0.3691
PVC				
ROUGHNESS (mic)	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
0.06	6.90E-10	0.3937	8.97E-10	0.4403
0.12	5.86E-10	0.3737	5.52E-10	0.4286
0.15	7.10E-10	0.3859	6.90E-10	0.3925
0.18	7.59E-10	0.3582	7.59E-10	0.3456
0.21	8.62E-10	0.3367	1.01E-09	0.3386
0.30	1.24E-09	0.3252	1.38E-09	0.3092
0.36	1.79E-09	0.2513	1.66E-09	0.2836

Test Conditions:

Nylon: *Speed: 0.5 m/s; Time: 18000 sec; Counterface Roughness: 0.15 microns*
Teflon(v): *Load: 88.96 N; Time: 6000 sec; Counterface Roughness: 0.13 microns*
HDPE: *Load: 88.96 N; Speed: 0.5 m/s; Counterface Roughness: 0.13 microns*
PVC: *Load: 88.96 N; Speed: 0.5 m/s; Time: 18000 sec*

TABLE A.3.17. : Wear volume and Coefficient of friction of different polymers sliding against AISI 1018 steel at different disk speeds (rpm) at counterface roughness 0.13 microns

WEAR VOLUME (cu.m)					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
UHMWPE	5.31E-11	5.31E-11	5.31E-11	5.31E-11	5.31E-11
Delrin	1.41E-10	1.41E-10	1.76E-10	1.41E-10	2.11E-10
PVC	2.76E-10	2.76E-10	2.76E-10	2.76E-10	2.76E-10
Rulon	3.54E-10	3.54E-10	3.54E-10	3.54E-10	3.54E-10
Nylatron GS	1.03E-09	1.38E-09	1.47E-09	1.47E-09	1.21E-09
LDPE	6.50E-09	7.59E-09	8.24E-09	9.00E-09	8.56E-09
Teflon (v)*	1.24E-07	1.21E-07	1.13E-07	1.13E-07	1.06E-07
Teflon (m)*	1.26E-07	1.47E-07	1.45E-07	1.32E-07	1.22E-07
COEFFICIENT OF FRICTION					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
UHMWPE	0.2139	0.2053	0.1880	0.1898	0.1963
Delrin	0.3432	0.3706	0.3466	0.3474	0.3698
PVC	0.3751	0.3499	0.3527	0.3464	0.3411
Rulon	0.2431	0.2525	0.2572	0.2397	0.2384
Nylatron GS	0.3682	0.3850	0.3920	0.3709	0.3733
LDPE	0.5095	0.5081	0.5124	0.5209	0.5099
Teflon (v)*	0.2737	0.2619	0.2497	0.2737	0.2977
Teflon (m)*	0.2506	0.2613	0.2626	0.2580	0.2472

Test Conditions: *Load: 88.96 N; Surface Sliding Speed: 0.5 m/s; Time: 18000 sec, {*: 6000 sec}; Counterface Roughness: 0.13 microns*

TABLE A.3.18. : Wear volume and Coefficient of friction of different polymers sliding against AISI 1018 steel at different disk speeds (rpm) at counterface roughness 0.26 microns

WEAR VOLUME (cu.m)					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
Foulton	5.19E-10	5.19E-10	5.19E-10	5.19E-10	5.19E-10
Rulon	5.31E-10	6.64E-10	5.31E-10	5.75E-10	4.87E-10
PVC	7.59E-10	7.24E-10	7.79E-10	7.24E-10	7.24E-10
Nylon	1.22E-09	1.30E-09	1.30E-09	1.30E-09	1.30E-09
Nylatron GS	1.29E-09	1.38E-09	1.29E-09	1.38E-09	1.38E-09
HDPE	1.89E-09	1.89E-09	1.68E-09	2.10E-09	1.99E-09
LDPE	1.18E-08	1.13E-08	1.17E-08	1.28E-08	1.20E-08
Polypropylene*	9.59E-09	1.04E-08	9.92E-09	1.29E-08	1.22E-08
Polycarbonate**	6.67E-09	7.50E-09	6.83E-09	8.67E-09	7.33E-09
Teflon (v)***	1.12E-07	1.04E-07	9.47E-08	1.01E-07	9.92E-08
COEFFICIENT OF FRICTION					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
Foulton	0.2425	0.2527	0.2515	0.2554	0.2427
Rulon	0.2010	0.2018	0.2083	0.2039	0.2154
PVC	0.3121	0.2977	0.3017	0.3080	0.3152
Nylon	0.3324	0.3274	0.3261	0.3421	0.3421
Nylatron GS	0.3754	0.3678	0.3826	0.3809	0.3784
HDPE	0.2581	0.2617	0.2551	0.2607	0.2589
LDPE	0.4619	0.4775	0.4825	0.5150	0.4958
Polypropylene*	0.6001	0.5785	0.5616	0.6036	0.5462
Polycarbonate**	0.5926	0.5440	0.5932	0.6244	0.5460
Teflon (v)***	0.2147	0.1986	0.1874	0.1942	0.2027

Test Conditions: *Load: 88.96 N, {*: 45 N, **: 9 N}; Surface Sliding Speed: 0.5m/s; Time: 18000 sec, {***: 6000 sec}; Counterface Roughness: 0.26 microns*

TABLE A.3.19. : Wear volume and Coefficient of friction of different polymers sliding against HTSR 4140 steel at different disk speeds (rpm) at counterface roughness 0.13 microns

WEAR VOLUME (cu.m)					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
Rulon	3.10E-10	3.10E-10	3.10E-10	3.54E-10	3.98E-10
PVC	4.14E-10	4.14E-10	4.14E-10	4.14E-10	4.14E-10
Delrin	5.63E-10	5.63E-10	6.34E-10	6.34E-10	7.75E-10
Nylatron GS	1.12E-09	1.03E-09	1.12E-09	1.03E-09	9.48E-10
Nylon	1.22E-09	1.13E-09	1.16E-09	1.17E-09	1.30E-09
LDPE	7.22E-09	7.59E-09	7.05E-09	7.70E-09	7.05E-09
Polypropylene*	2.64E-09	3.31E-09	2.42E-09	3.09E-09	2.98E-09
Polycarbonate**	1.92E-09	1.33E-09	1.50E-09	1.83E-09	1.25E-09
Teflon (v)***	9.66E-08	8.95E-08	9.63E-08	9.52E-08	9.82E-08
Teflon (m)***	1.25E-07	1.08E-07	1.20E-07	1.04E-07	1.25E-07
COEFFICIENT OF FRICTION					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
Rulon	0.2353	0.2593	0.2478	0.2617	0.2372
PVC	0.3526	0.3828	0.3834	0.3927	0.3616
Delrin	0.4981	0.4968	0.4980	0.4872	0.5639
Nylatron GS	0.3826	0.3977	0.3902	0.3934	0.4149
Nylon	0.3506	0.3142	0.3414	0.3316	0.3269
LDPE	0.5295	0.5335	0.5204	0.5252	0.5270
Polypropylene*	0.6251	0.6477	0.6911	0.6221	0.6654
Polycarbonate**	0.6152	0.5472	0.5472	0.5529	0.4680
Teflon (v)***	0.2820	0.2796	0.2882	0.2926	0.3056
Teflon (m)***	0.2561	0.2481	0.2493	0.2496	0.2411

Test Conditions: *Load: 88.96 N, {*: 45 N, **: 9 N}; Surface Sliding Speed: 0.5m/s; Time: 18000 sec, {***: 6000 sec}; Counterface Roughness: 0.13 microns*

TABLE A.3.20. : Wear volume and Coefficient of friction of different polymers sliding against HTSR 4140 steel at different disk speeds (rpm) at counterface roughness 0.26 microns

WEAR VOLUME (cu.m)					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
UHMWPE	2.13E-10	2.13E-10	2.13E-10	2.13E-10	2.13E-10
Rulon	3.98E-10	3.54E-10	3.98E-10	3.54E-10	3.54E-10
Foulton	4.55E-10	5.19E-10	5.19E-10	4.55E-10	4.55E-10
Delrin	5.63E-10	5.63E-10	5.63E-10	6.34E-10	5.63E-10
PVC	9.66E-10	9.66E-10	8.28E-10	8.28E-10	8.28E-10
Nylatron GS	1.29E-09	1.21E-09	1.21E-09	1.21E-09	1.21E-09
Nylon	2.70E-09	2.52E-09	2.26E-09	3.83E-09	4.00E-09
LDPE	1.39E-08	1.58E-08	1.72E-08	2.17E-08	2.50E-08
Polycarbonate*	6.75E-09	8.08E-09	8.75E-09	1.00E-08	1.15E-08
Teflon (v)**	8.92E-08	9.01E-08	9.14E-08	8.56E-08	8.09E-08
COEFFICIENT OF FRICTION					
RPM of Disk	**78**	**90**	**102**	**125**	**155**
MATERIAL					
UHMWPE	0.1875	0.2055	0.1860	0.1954	0.1743
Rulon	0.2025	0.2201	0.2252	0.2192	0.2051
Foulton	0.2569	0.2478	0.2517	0.2428	0.2440
Delrin	0.3669	0.3368	0.3528	0.3843	0.3410
PVC	0.2940	0.3055	0.3116	0.3240	0.3212
Nylatron GS	0.4218	0.3821	0.4606	0.4399	0.4453
Nylon	0.2678	0.2708	0.2663	0.2674	0.2549
LDPE	0.4664	0.4814	0.4938	0.4994	0.4839
Polycarbonate*	0.5785	0.5689	0.5970	0.5718	0.5890
Teflon (v)**	0.2186	0.2189	0.2193	0.2188	0.2190

Test Conditions: *Load: 88.96 N, {*: 9 N}; Surface Sliding Speed: 0.5 m/s; Time: 18000 sec, {**: 3600 sec}; Counterface Roughness: 0.26 microns*

TABLE A.3.21. : Wear volume and Coefficient of friction of different polymers sliding against AISI 1018 steel at different sliding speeds for different counterface roughness

At roughness = 0.13 microns						
	0.25 m/s		**0.375 m/s**		**0.5 m/s**	
MATERIAL	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction
UHMWPE	5.31E-11	0.1920	1.06E-10	0.2129	1.59E-10	0.1880
Rulon	1.33E-10	0.1927	2.65E-10	0.2328	3.54E-10	0.2572
PVC	1.72E-10	0.4200	2.41E-10	0.3689	2.76E-10	0.3527
Nylatron GS	2.59E-10	0.3378	6.03E-10	0.4019	1.47E-09	0.3920
LDPE	4.88E-09	0.5073	6.18E-09	0.5025	8.24E-09	0.5124
At roughness = 0.26 microns						
	0.25 m/s		**0.375 m/s**		**0.5 m/s**	
MATERIAL	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction
Foulton	1.95E-10	0.2454	3.25E-10	0.2619	5.19E-10	0.2515
Rulon	3.10E-10	0.1957	3.98E-10	0.1928	5.31E-10	0.2083
PVC	4.48E-10	0.3390	5.52E-10	0.2928	7.79E-10	0.3017
Nylon	4.96E-10	0.3448	6.70E-10	0.3382	1.30E-09	0.3261
HDPE	4.20E-10	0.2302	1.05E-09	0.2410	1.68E-09	0.2551
LDPE	7.05E-09	0.4785	9.32E-09	0.4810	1.17E-08	0.4825
Polycarbonate*	2.92E-09	0.6215	4.33E-09	0.6559	6.83E-09	0.6215
Teflon (v)**	6.41E-08	0.2165	9.26E-08	0.2376	9.47E-08	0.1874

Test Conditions: *Load: 88.96 N, {*: 9 N}; Time: 18000 sec, {**: 3600 sec}*

TABLE A.3.22. : Wear volume and Coefficient of friction of different polymers sliding against HTSR 4140 steel at different sliding speeds for different counterface roughness

At 0,13 roughness = microns

	0.25 m/s		0.375 m/s		0.5 m/s	
MATERIAL	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction
PVC	2.07E-10	0.4219	2.76E-10	0.3984	4.83E-10	0.3834
Rulon	2.21E-10	0.2360	2.65E-10	0.2521	3.10E-10	0.2428
Nylon	2.61E-10	0.3479	3.91E-10	0.3685	1.16E-09	0.3414
Nylatron GS	4.31E-10	0.3826	1.03E-09	0.3747	1.12E-09	0.3902
LDPE	3.47E-09	0.4884	4.34E-09	0.5016	7.05E-09	0.5204
Polycarbonate*	5.00E-10	0.7044	6.67E-10	0.6877	1.38E-09	0.5472

At roughness = 0.26 microns

	0.25 m/s		0.375 m/s		0.5 m/s	
MATERIAL	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction	WearVol.cu.m	Co.of Friction
UHMWPE	5.31E-11	0.1768	1.06E-10	0.2006	2.13E-10	0.1860
Delrin	2.11E-10	0.3294	2.82E-10	0.3166	4.93E-10	0.3528
Foulton	2.60E-10	0.2488	3.90E-10	0.2618	4.55E-10	0.2519
Rulon	2.65E-10	0.2116	3.10E-10	0.2061	4.42E-10	0.2252
Nylon	1.04E-09	0.2995	1.39E-09	0.3144	2.17E-09	0.2663
LDPE	8.56E-09	0.4562	1.17E-08	0.4242	1.72E-08	0.4938
Polycarbonate*	4.17E-09	0.6052	5.75E-09	0.4954	8.75E-09	0.5970
Teflon (v)**	6.08E-08	0.2231	7.33E-08	0.2234	9.14E-08	0.2193

Test Conditions: *Load: 88.96 N, {*: 9 N}; Time: 18000 sec, {**: 3600 sec}*

TABLE A.3.23. : Wear volume and Coefficient of friction of different polymers sliding against AISI 1018 steel at different loads for different counterface roughness

At roughness = 0.13microns				
	90 N		**135 N**	
MATERIAL	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
UHMWPE	5.31E-11	0.2139	2.13E-10	0.1839
PVC	2.76E-10	0.3751	6.90E-10	0.3445
Rulon	3.54E-10	0.2431	4.87E-10	0.2416
Nylatron GS	1.03E-09	0.3682	2.07E-09	0.3845
LDPE	6.50E-09	0.5099	2.08E-08	0.5075
At roughness = 0.26 microns				
	90 N		**135 N**	
MATERIAL	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
Foulton	5.19E-10	0.2425	6.49E-10	0.2469
Rulon	5.31E-10	0.2010	7.08E-10	0.2027
PVC	7.59E-10	0.3121	2.07E-09	0.2842
Nylon	1.22E-09	0.3324	2.00E-09	0.3071
HDPE	1.89E-09	0.2581	5.46E-09	0.2661
LDPE	1.18E-08	0.4619	2.34E-08	0.4968
Polypropylene*	9.59E-09	0.6001	2.92E-08	0.6476
Polycarbonate**	6.67E-09	0.5926	1.58E-08	0.5469

Test Conditions: *Surface Sliding Speed: 0.5 m/s; Time: 18000 sec*
*{Load: *: 45 and 72 N, **: 9 and 18 N}*

TABLE A.3.24. : Wear volume and Coefficient of friction of different polymers sliding against HTSR 4140 steel at different loads for different counterface roughness

At roughness = 0.13 microns				
	90 N		135 N	
MATERIAL	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
Rulon	3.10E-10	0.2353	5.31E-10	0.2421
PVC	4.14E-10	0.3526	5.52E-10	0.3505
Nylatron GS	1.12E-09	0.3826	1.72E-09	0.3742
Nylon	1.22E-09	0.3506	2.00E-09	0.3261
LDPE	6.72E-09	0.5295	2.17E-08	0.5268
At roughness = 0.26 microns				
	90 N		135 N	
MATERIAL	Wear Vol. (cu.m)	Co. of Friction	Wear Vol. (cu.m)	Co. of Friction
UHMWPE	2.13E-10	0.1875	4.25E-10	0.1674
Rulon	3.98E-10	0.2025	4.87E-10	0.1948
Foulton	4.55E-10	0.2569	7.14E-10	0.2437
Delrin	5.63E-10	0.3669	8.45E-10	0.3193
PVC	9.66E-10	0.2940	1.52E-09	0.2933
Nylon	2.70E-09	0.2678	3.39E-09	0.2754
LDPE	1.39E-08	0.4664	2.82E-08	0.4895
Polycarbonate*	6.75E-09	0.5785	1.90E-08	0.5514

Test Conditions: *Surface Sliding Speed: 0.5 m/s; Time: 18000 sec*
*{Load: *: 9 and 18 N}*

TABLE A.3.25. : Comparison of wear volume and coefficient of friction of different polymers sliding against AISI 1018 steel and HTSR 4140 steel in horizontal pin-on-disk and vertical pin-on-disk configurations

WEAR VOLUME:				
	MILD STEEL		**HTSR 4140 STEEL**	
MATERIAL	**VERTICAL PIN-ON-DISK**	**HORIZONTAL PIN-ON-DISK**	**VERTICAL PIN-ON-DISK**	**HORIZONTAL PIN-ON-DISK**
UHMWPE	5.31E-11	1.06E-10	1.13E-10	1.06E-10
Foulton	2.06E-10	2.40E-10	2.60E-10	2.60E-10
Rulon	3.54E-10	3.98E-10	3.10E-10	3.54E-10
Delrin	1.76E-10	7.04E-10	6.34E-10	8.45E-10
PVC	2.76E-10	7.59E-10	4.14E-10	7.59E-10
Nylon	1.30E-09	3.10E-09	1.60E-09	3.04E-09
Nylatron GS	1.47E-09	3.92E-09	1.12E-09	3.36E-09
HDPE	1.68E-09	4.72E-09	1.72E-09	3.78E-09
LDPE	4.88E-09	1.45E-08	8.47E-09	1.63E-08
Teflon(v)	1.13E-07	1.23E-07	9.63E-08	1.65E-07
Teflon(m)	1.45E-07	1.82E-07	1.20E-07	1.35E-07
COEFFICIENT OF FRICTION:				
	MILD STEEL		**HTSR 4140 STEEL**	
MATERIAL	**VERTICAL PIN-ON-DISK**	**HORIZONTAL PIN-ON-DISK**	**VERTICAL PIN-ON-DISK**	**HORIZONTAL PIN-ON-DISK**
UHMWPE	0.1880	0.2187	0.1860	0.2222
Rulon	0.2572	0.2296	0.2478	0.2386
Teflon(v)	0.2497	0.2297	0.2882	0.2698
Teflon(m)	0.2497	0.2598	0.2493	0.2405
HDPE	0.2551	0.3061	0.2461	0.2921
Foulton	0.3920	0.3064	0.2517	0.3256
PVC	0.3527	0.3582	0.3834	0.3456
Nylon	0.3261	0.4915	0.3414	0.4088
Delrin	0.4966	0.5326	0.4980	0.4899
Nylatron GS	0.3920	0.5747	0.3902	0.5068
LDPE	0.5073	0.6145	0.4884	0.6248

Test Conditions: *Load: 88.96 N; Surface Sliding Speed: 0.5 m/s, {*: 0.25 m/s}; Time: 18000 sec, {**: 6000 sec}; Counterface Roughness: 0.15 microns*

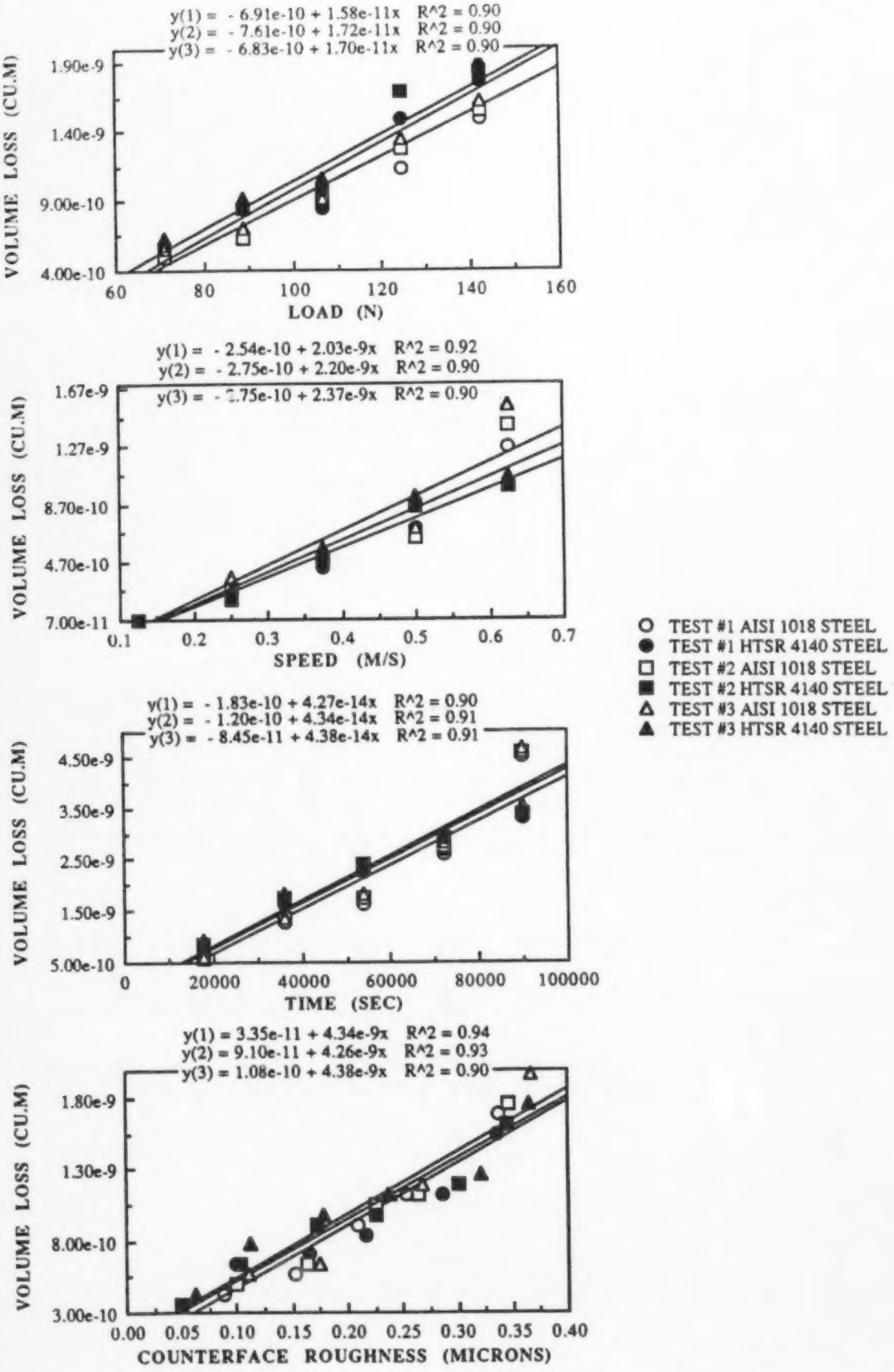

Fig. A.3.1: Volume loss vs. Operating variables for Delrin on linear coordinates with best fit straight lines for each set of tests against both counterfaces

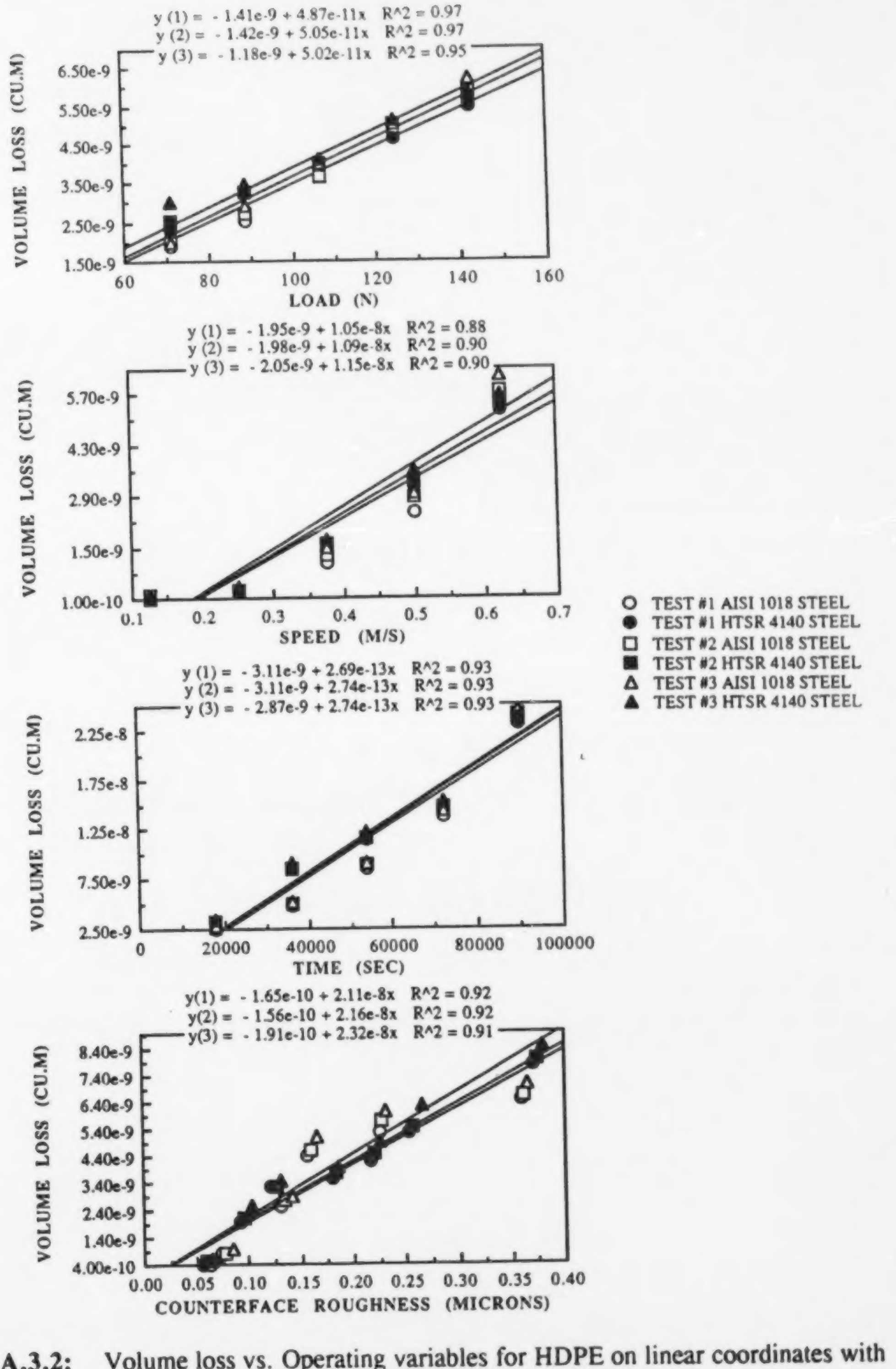

Fig. A.3.2: Volume loss vs. Operating variables for HDPE on linear coordinates with best fit straight lines for each set of tests against both counterfaces

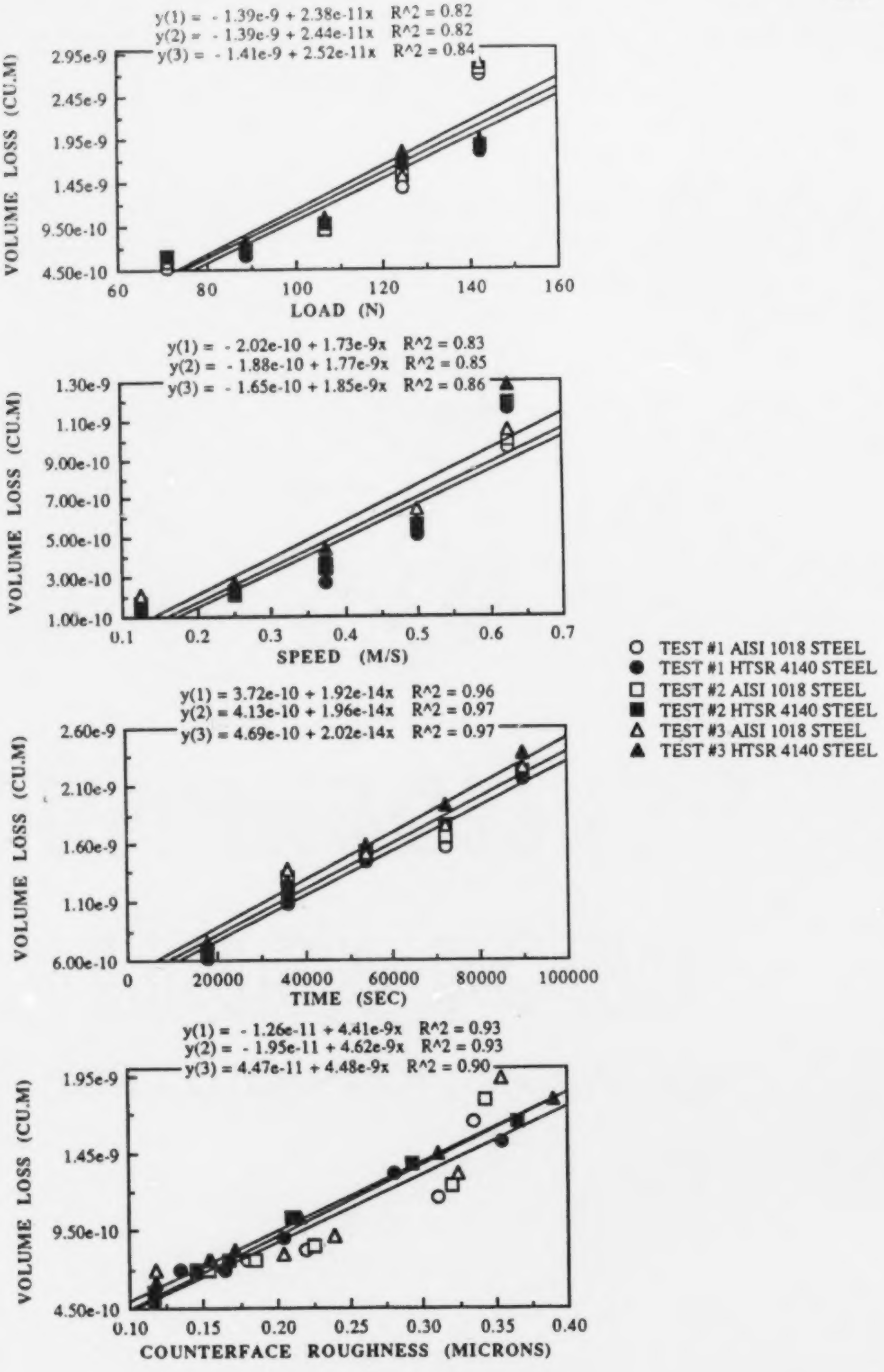

Fig. A.3.3: Volume loss vs. Operating variables for PVC on linear coordinates with best fit straight lines for each set of tests against both counterfaces

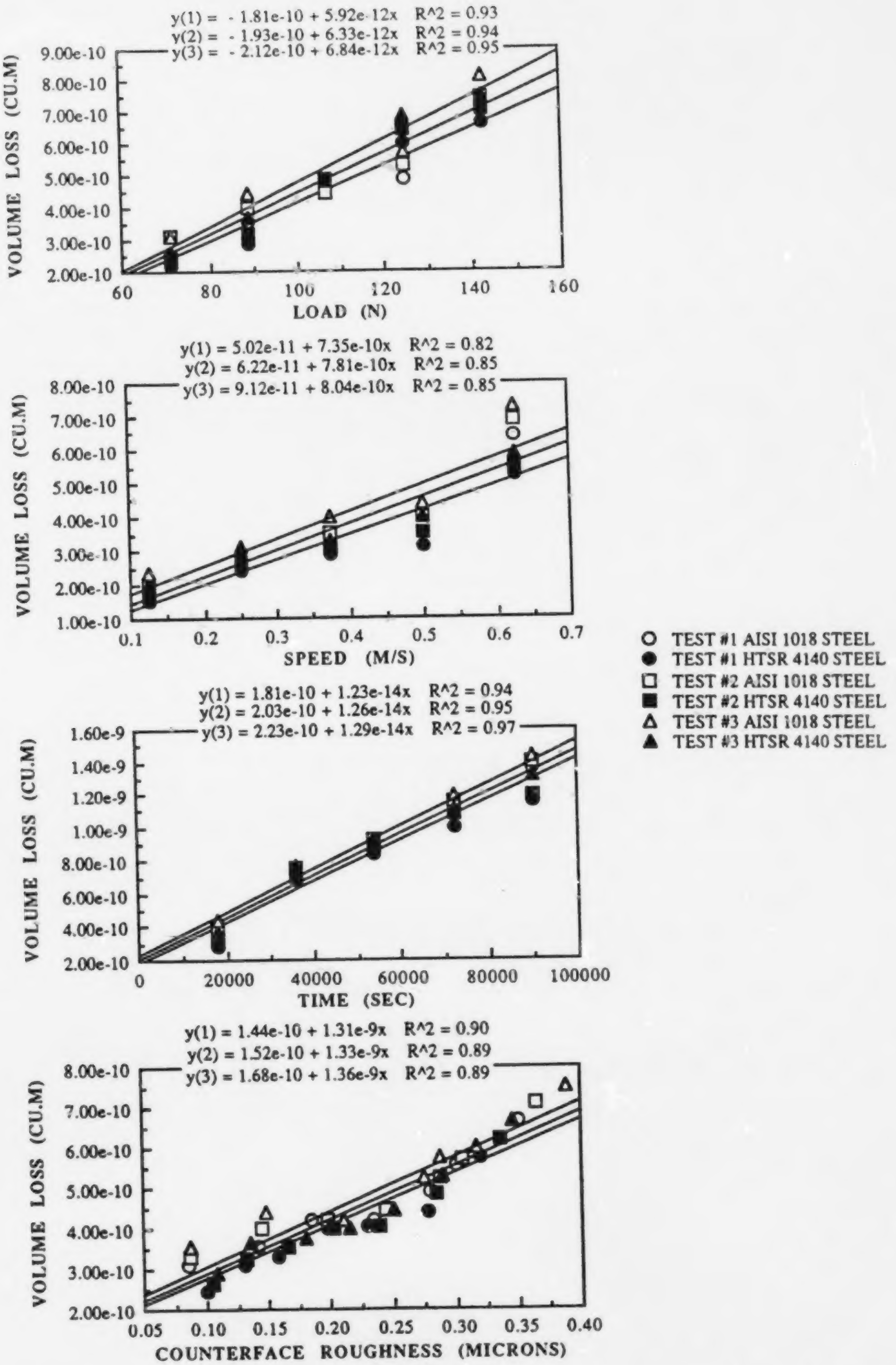

Fig. A.3.4: Volume loss vs. Operating variables for Rulon on linear coordinates with best fit straight lines for each set of tests against both counterfaces

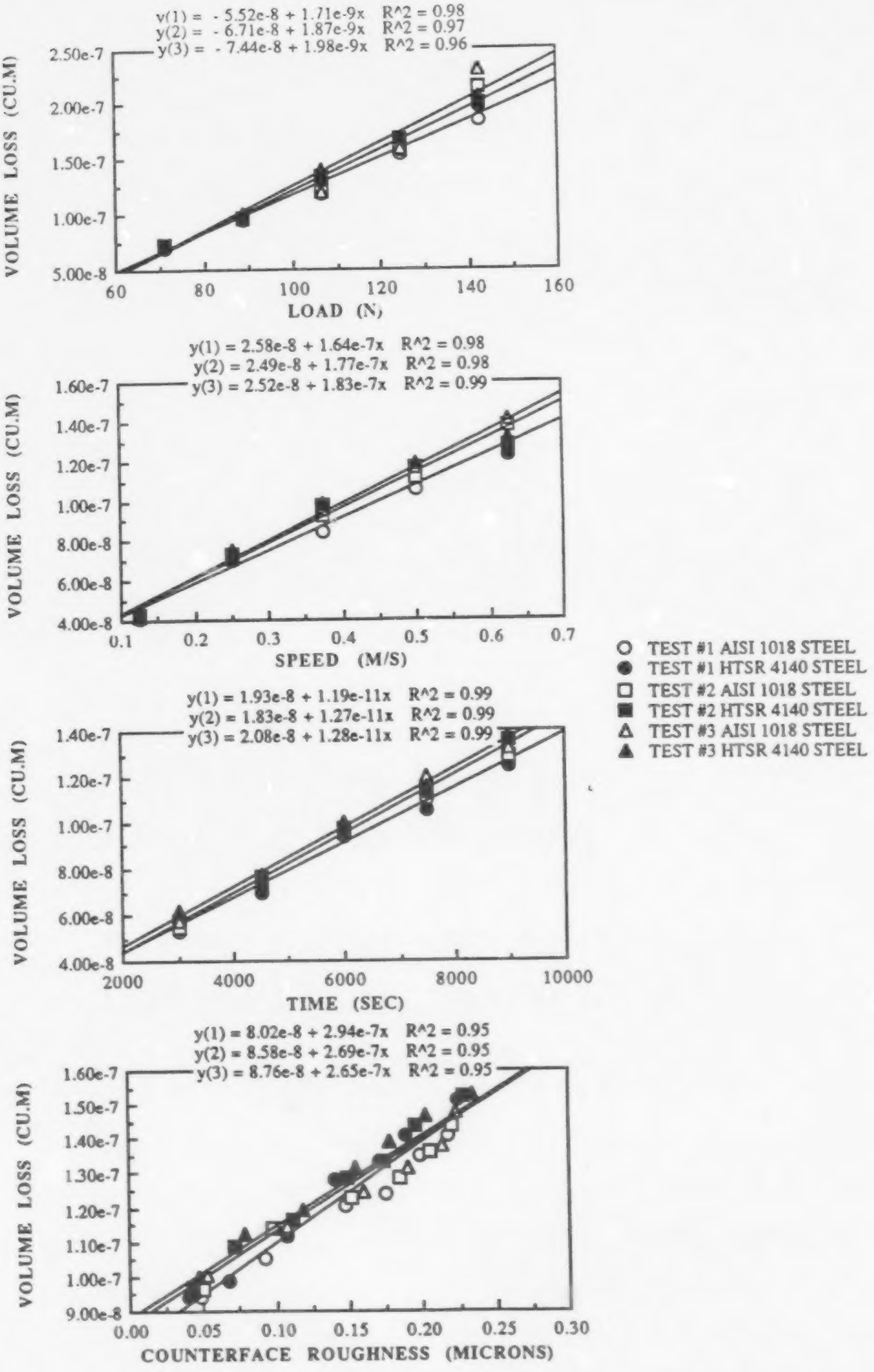

Fig. A.3.5: Volume loss vs. Operating variables for Teflon(m) on linear coordinates with best fit straight lines for each set of tests against both counterfaces

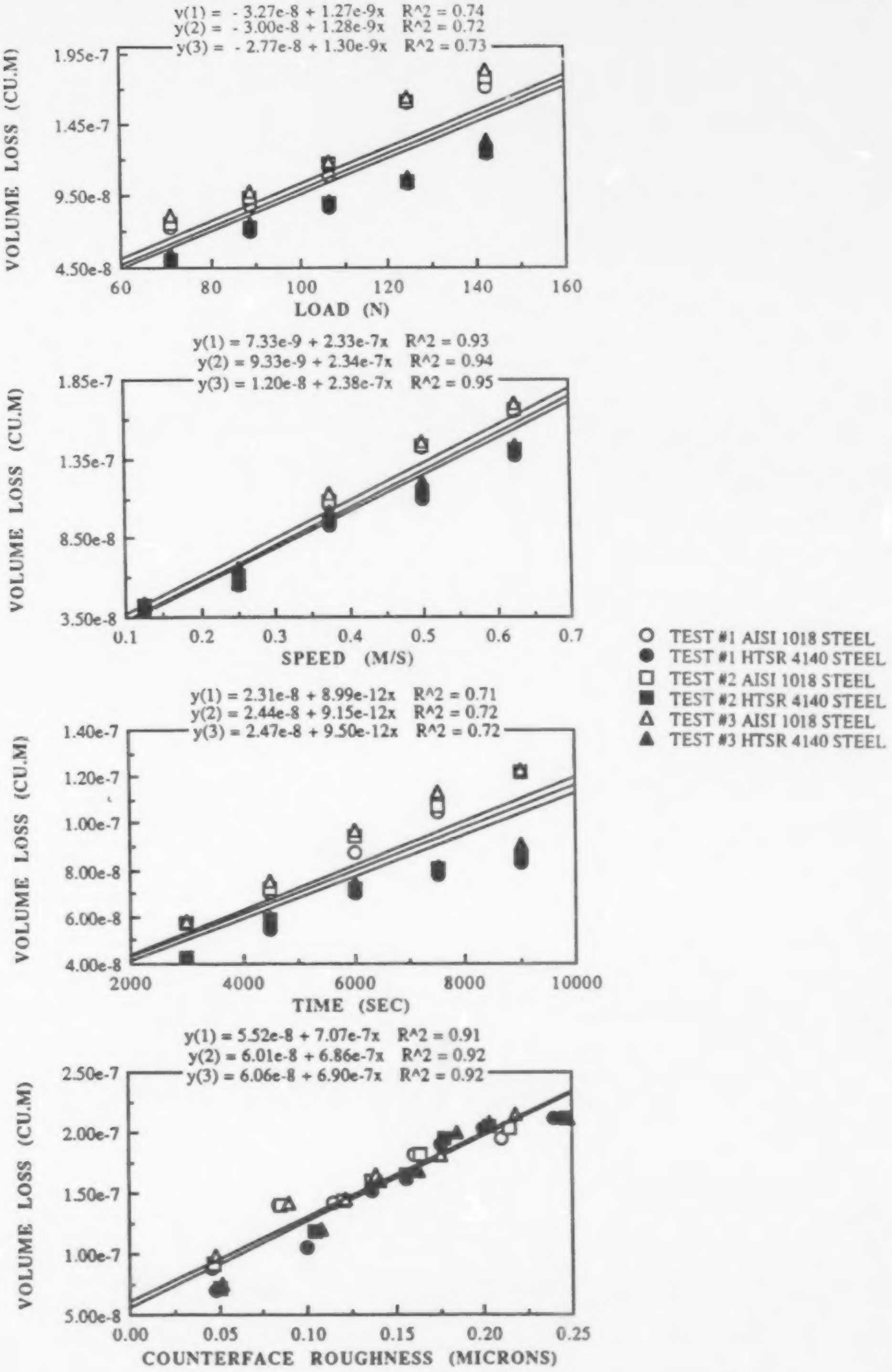

Fig. A.3.6: Volume loss vs. Operating variables for Teflon(v) on linear coordinates with best fit straight lines for each set of tests against both counterfaces

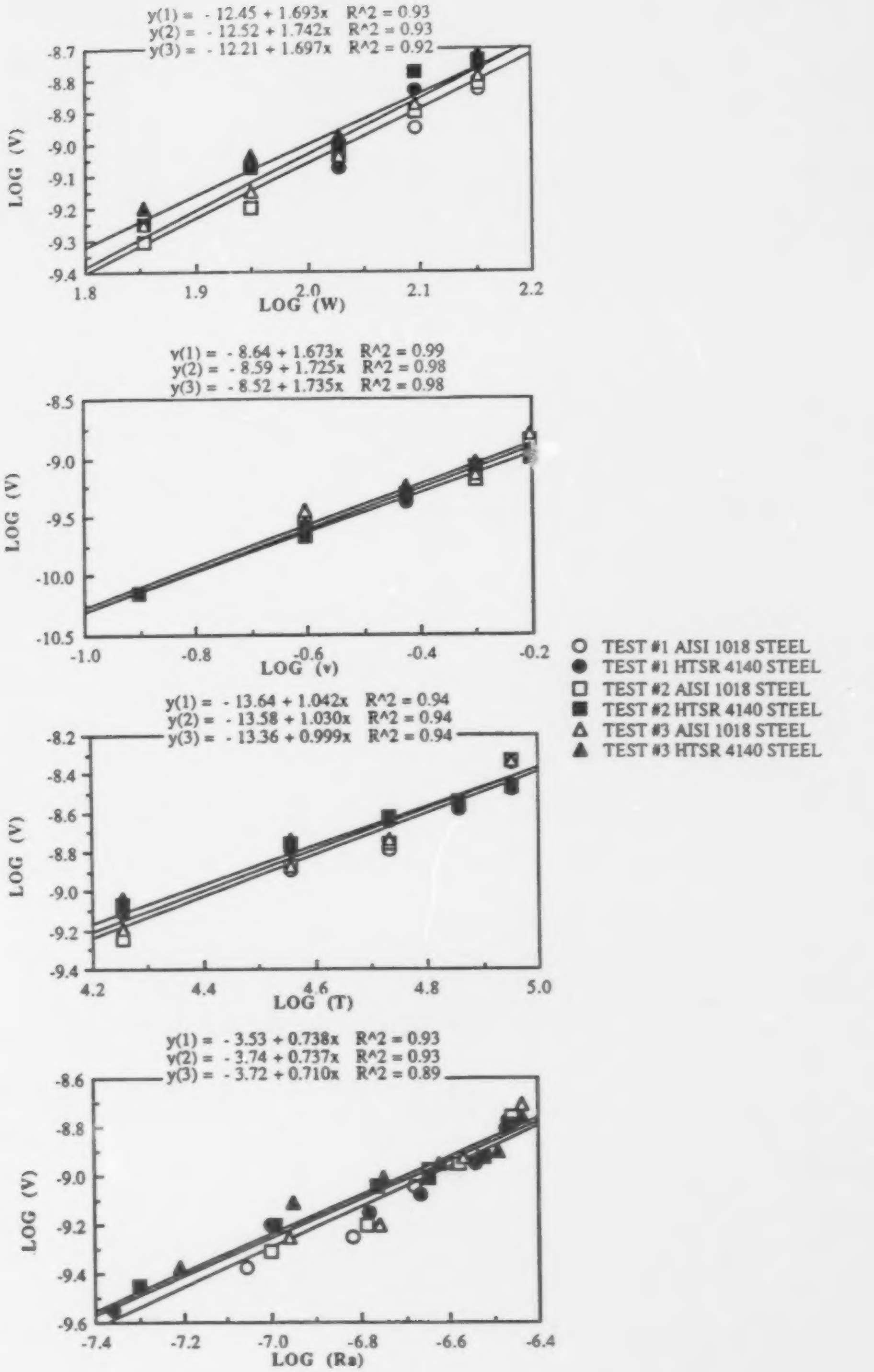

Fig. A.3.7: Volume loss vs. Operating variables for Delrin on logarithmic coordinates with best fit straight lines for each set of tests against both counterfaces

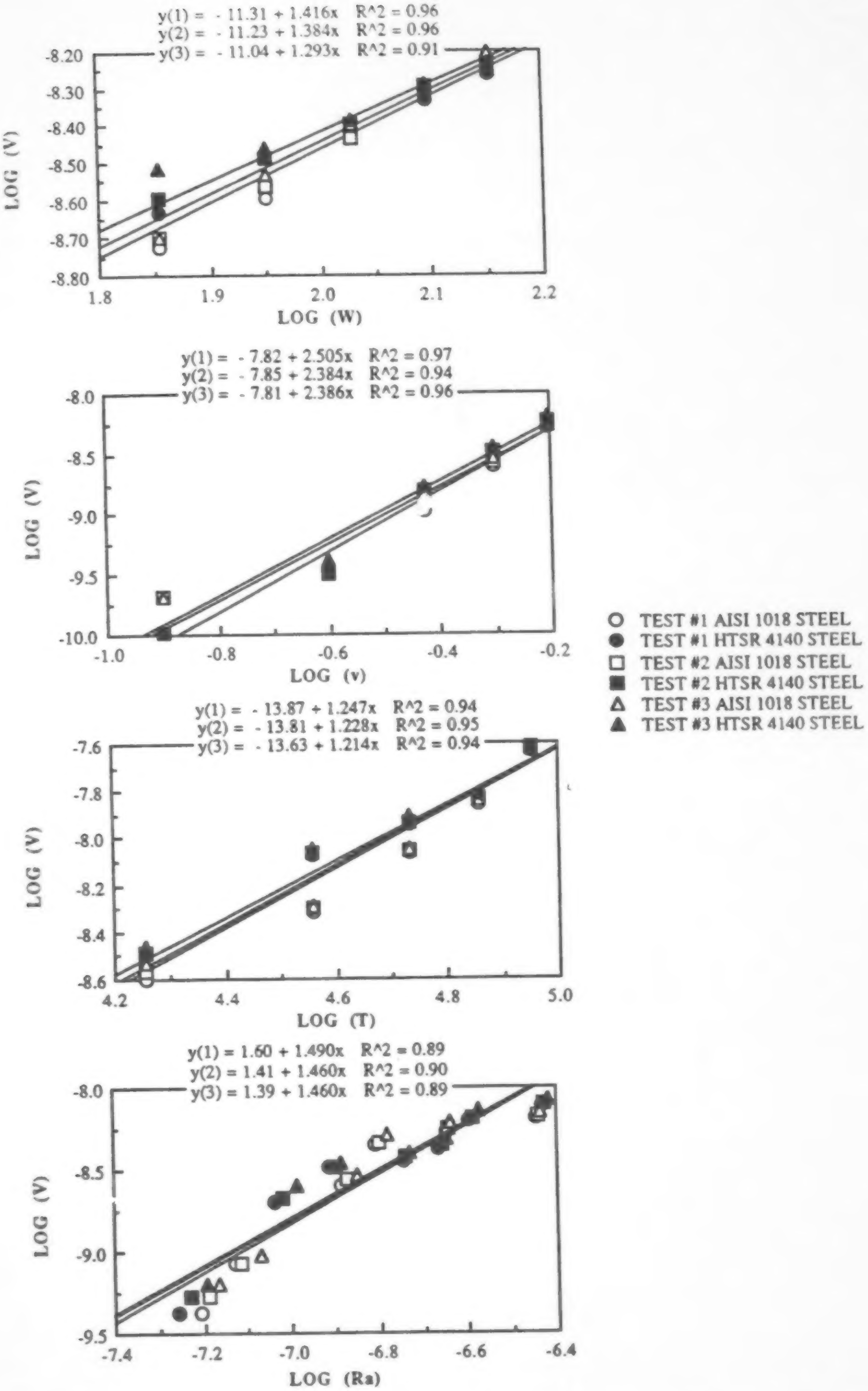

Fig. A.3.8: Volume loss vs. Operating variables for HDPE on logarithmic coordinates with best fit straight lines for each set of tests against both counterfaces

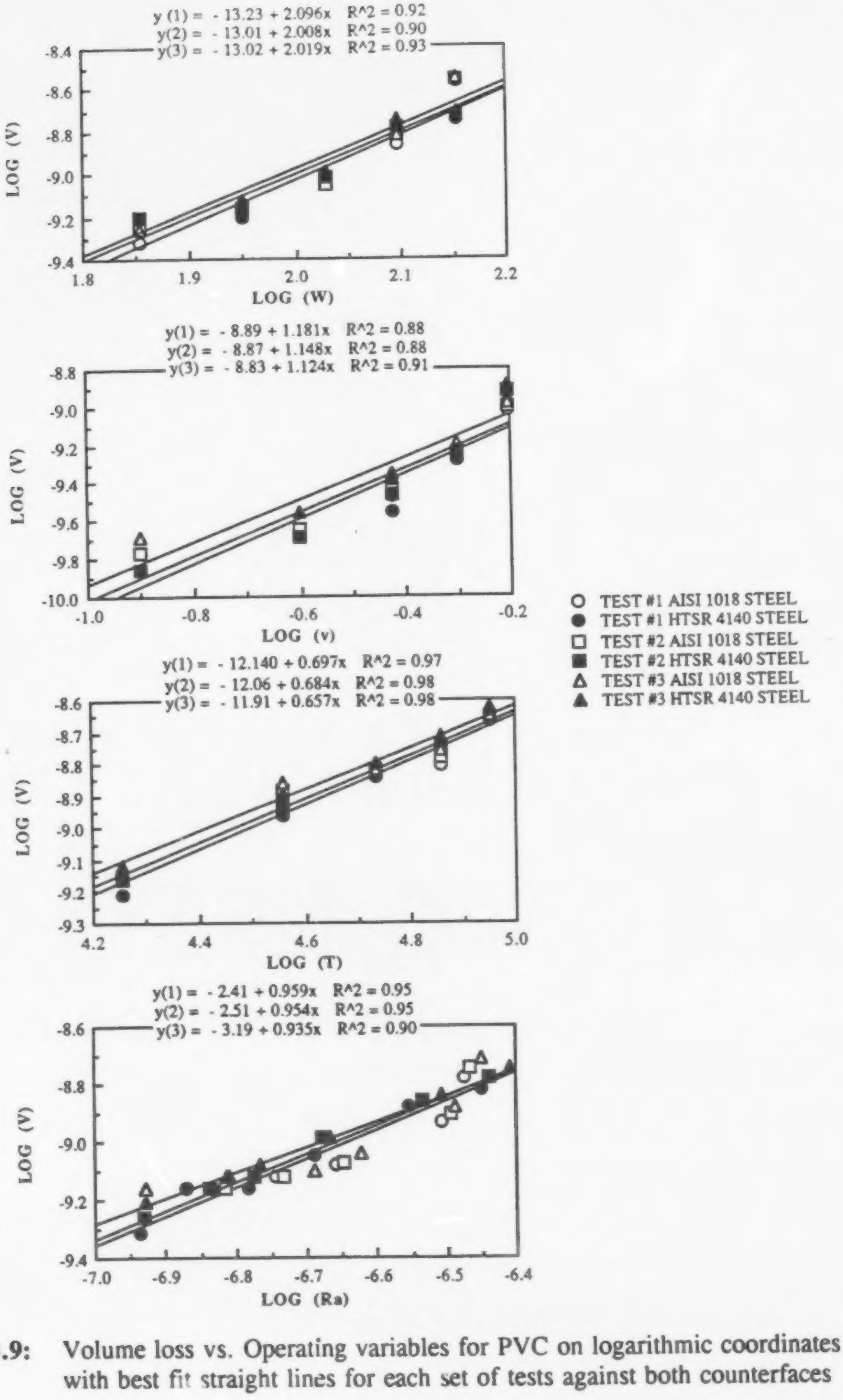

Fig. A.3.9: Volume loss vs. Operating variables for PVC on logarithmic coordinates with best fit straight lines for each set of tests against both counterfaces

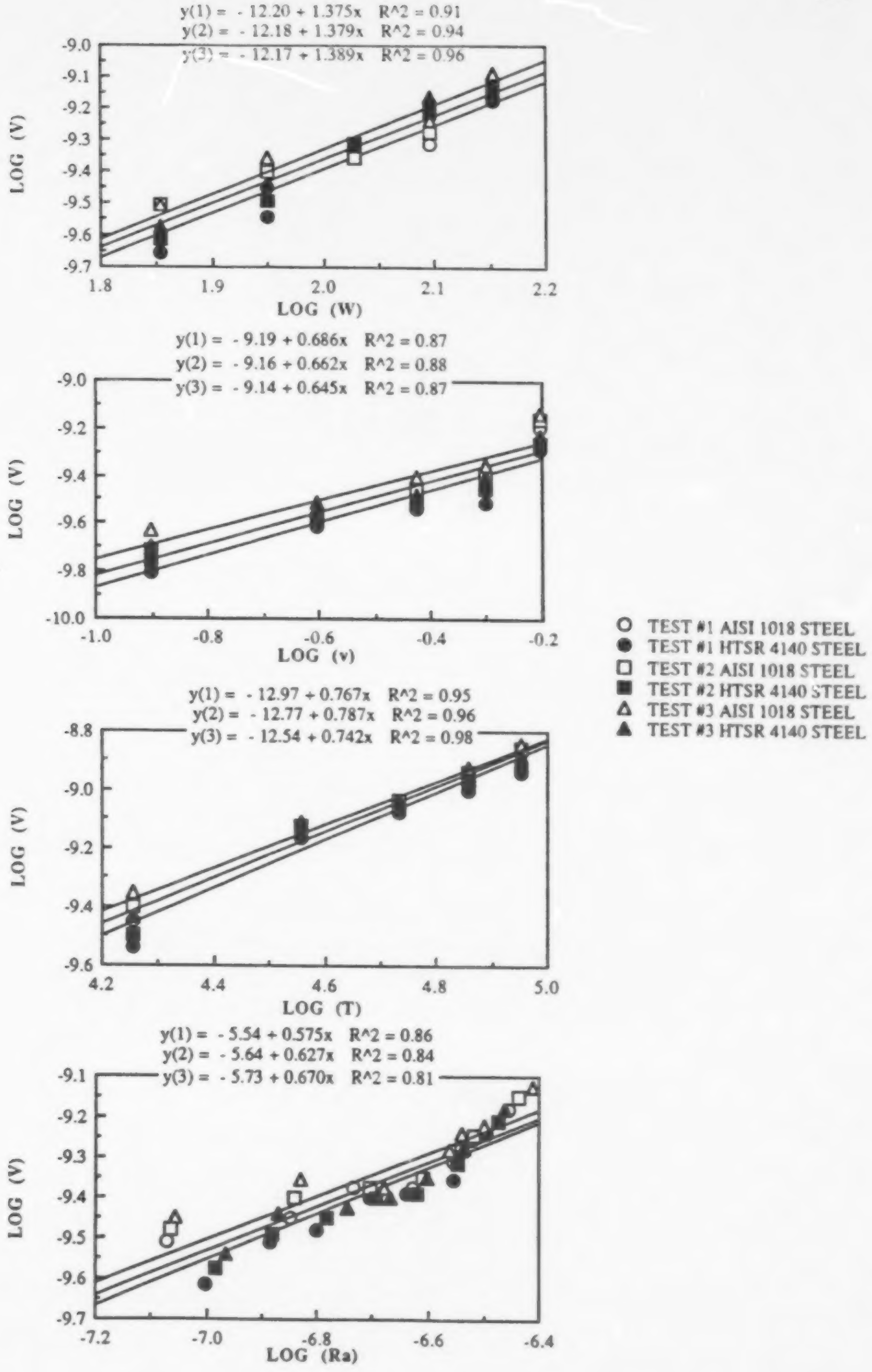

Fig. A.3.10: Volume loss vs. Operating variables for Rulon on logarithmic coordinates with best fit straight lines for each set of tests against both counterfaces

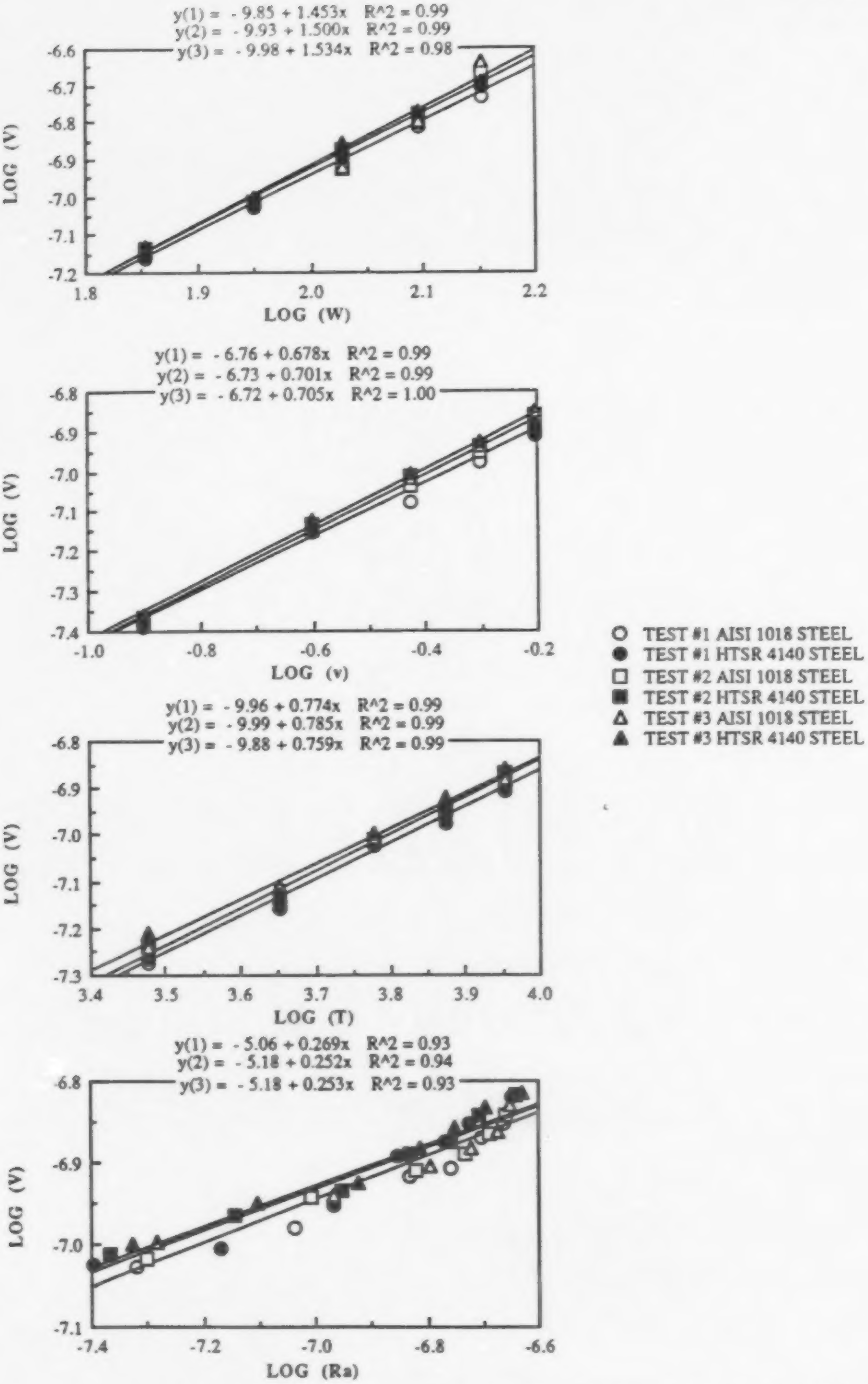

Fig. A.3.11: Volume loss vs. Operating variables for Teflon(m) on logarithmic coordinates with best fit straight lines for each set of tests against both counterfaces

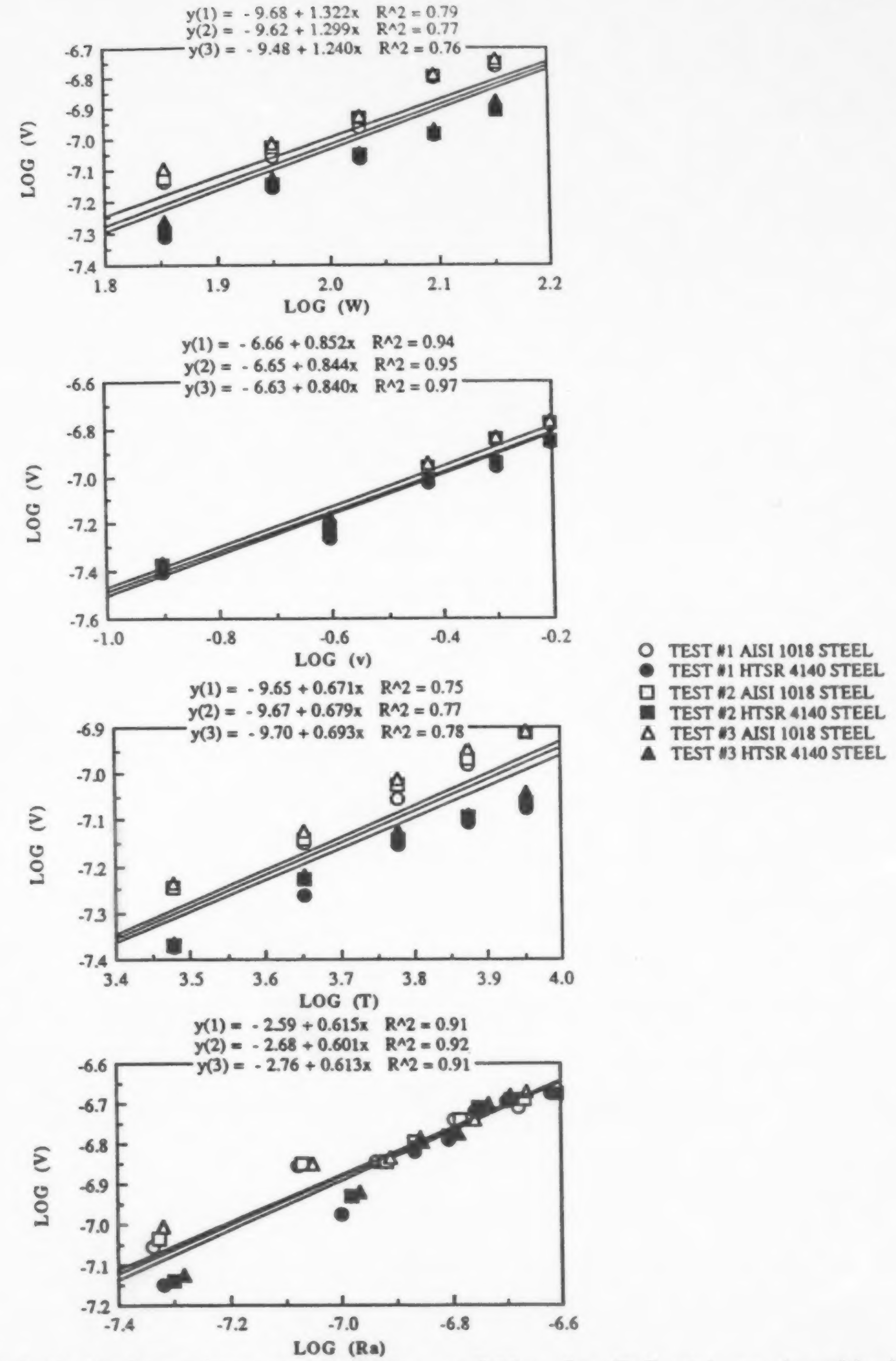

Fig. A.3.12: Volume loss vs. Operating variables for Teflon(v) on logarithmic coordinates with best fit straight lines for each set of tests against both counterfaces

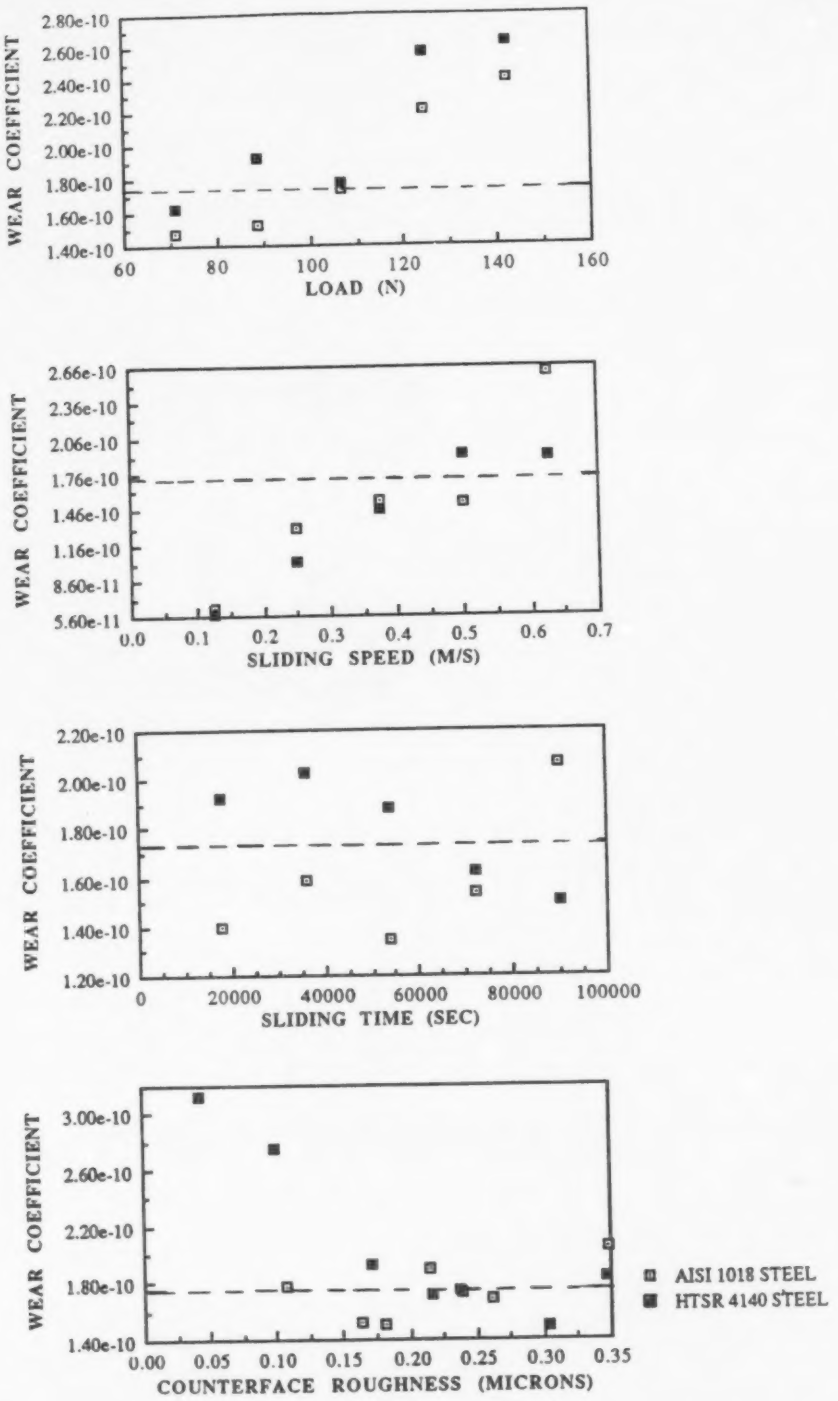

Fig. A.3.13: Sensitivity of the wear coefficient of delrin with the operating variables and scatter from the average wear coefficient (dotted line) for the linear model

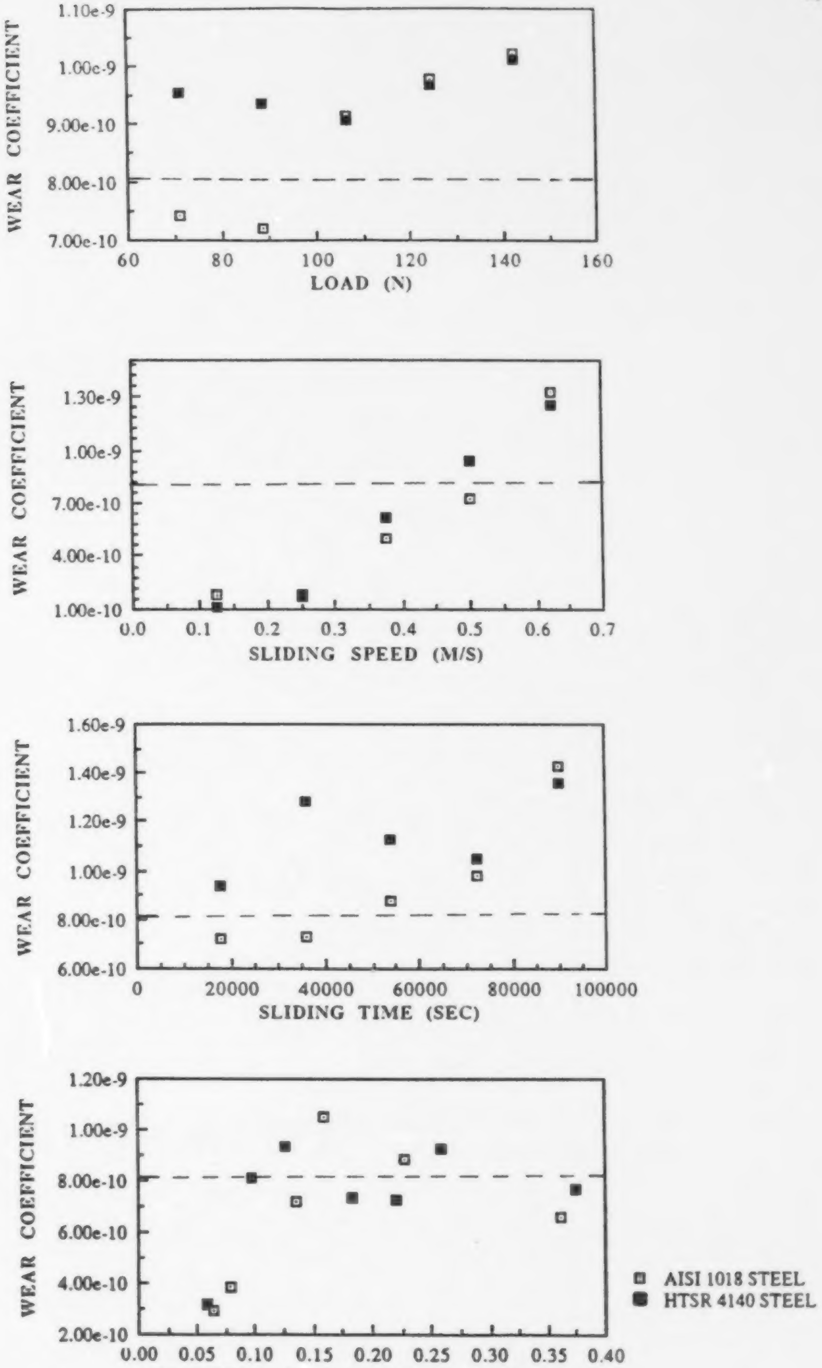

Fig. A.3.14: Sensitivity of the wear coefficient of HDPE with the operating variables and scatter from the average wear coefficient (dotted line) for the linear model

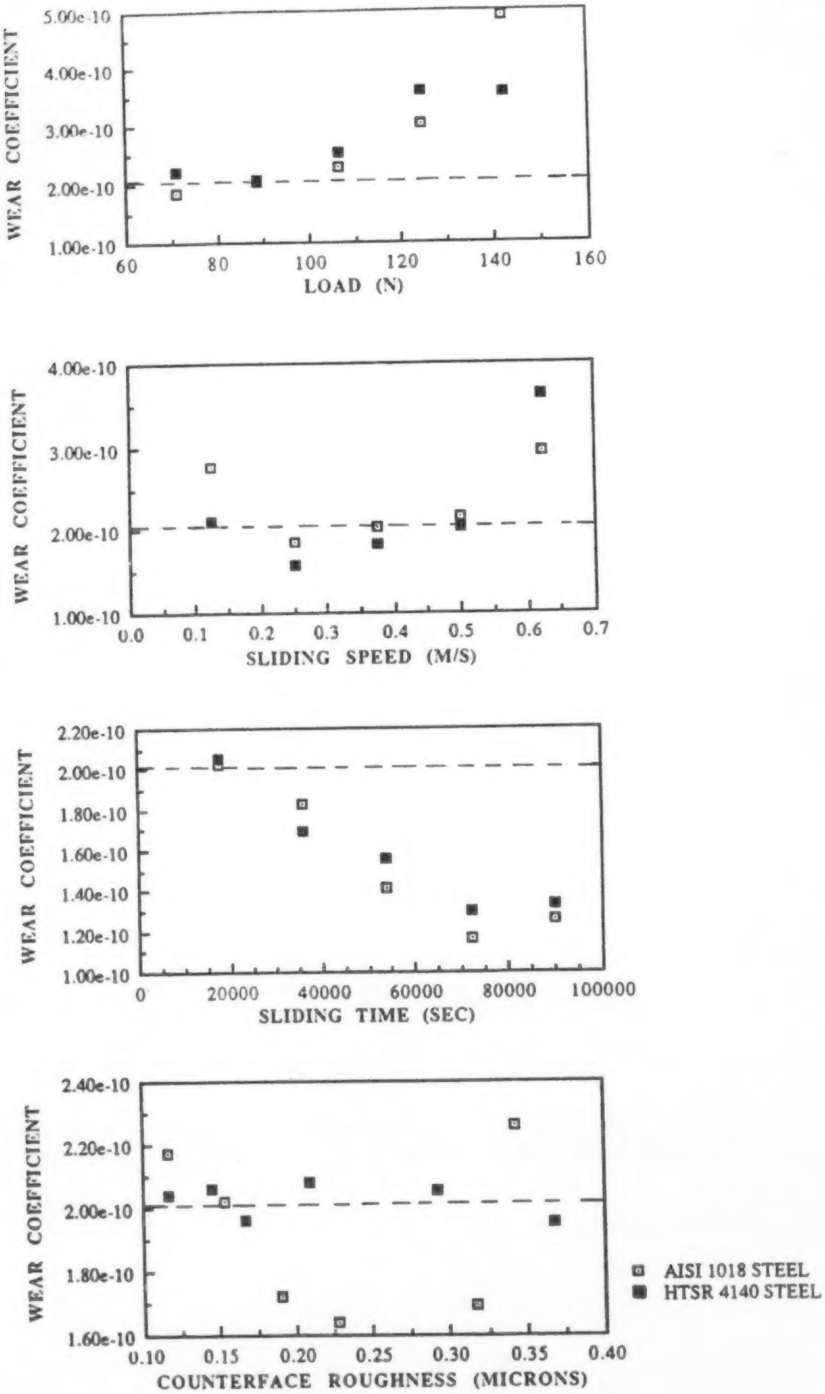

Fig. A.3.15: Sensitivity of the wear coefficient of PVC with the operating variables and scatter from the average wear coefficient (dotted line) for the linear model

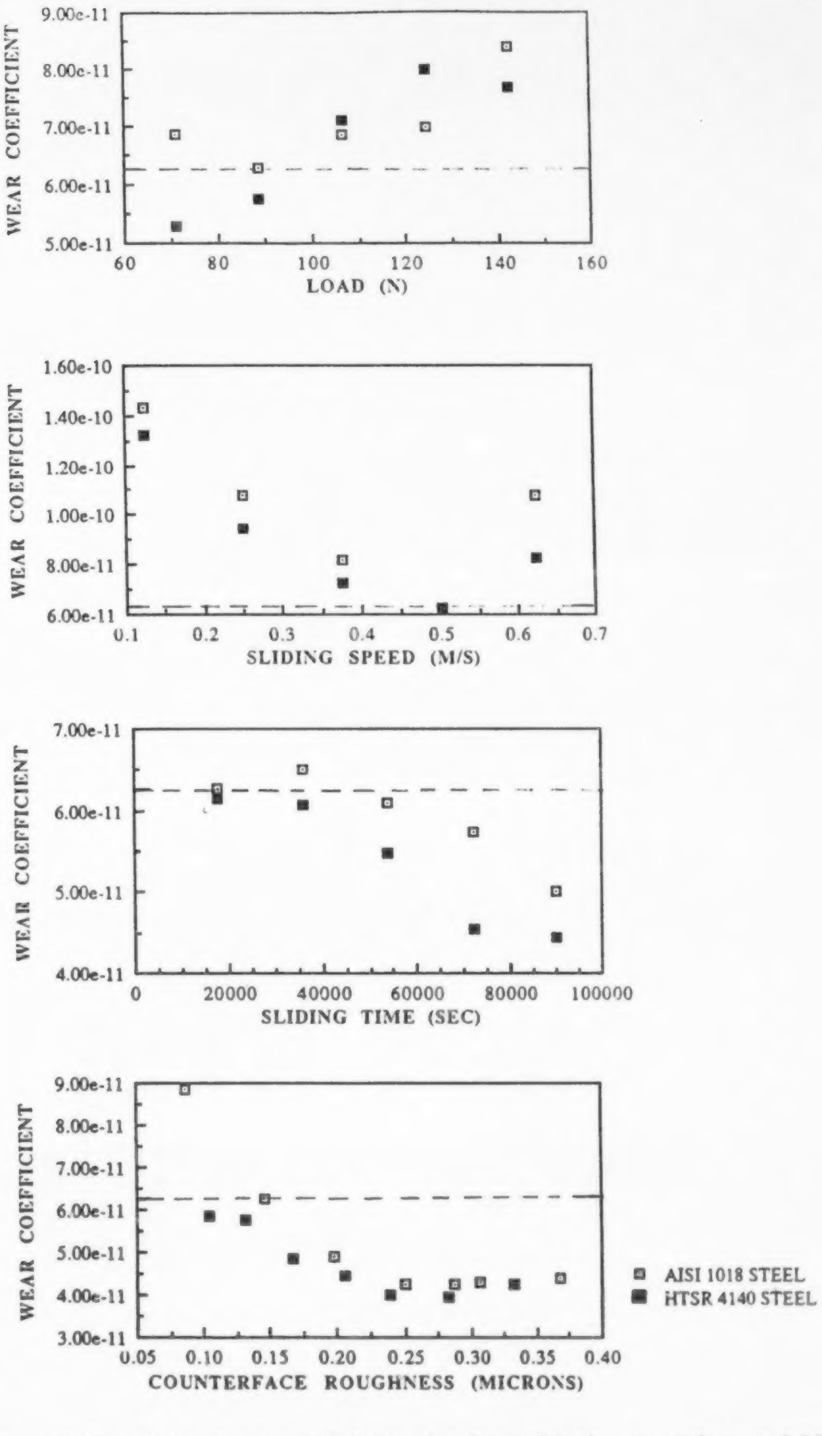

Fig. A.3.16: Sensitivity of the wear coefficient of rulon with the operating variables and scatter from the average wear coefficient (dotted line) for the linear model

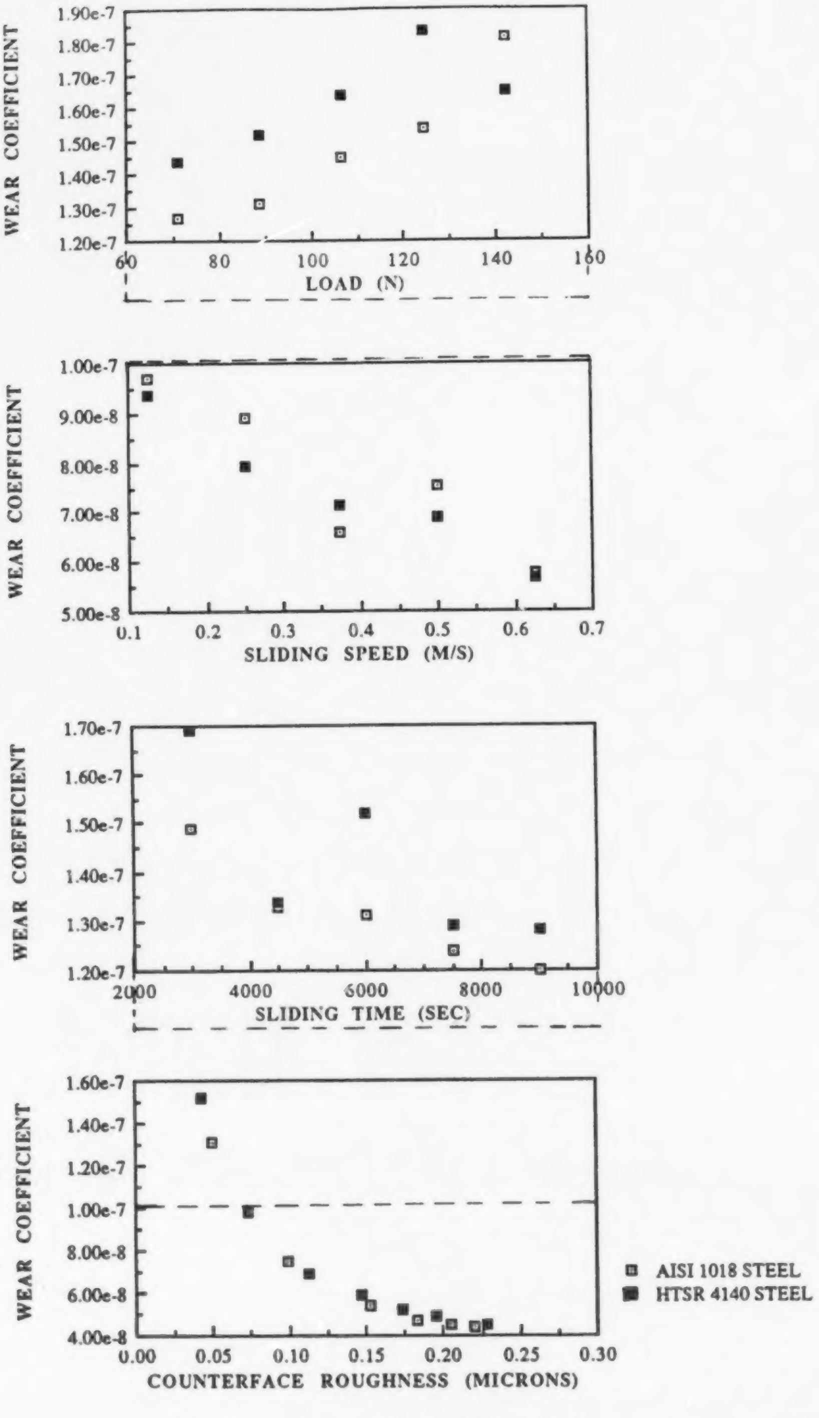

Fig. A.3.17: Sensitivity of the wear coefficient of teflon(m) with the operating variables and scatter from the average wear coefficient (dotted line) for the linear model

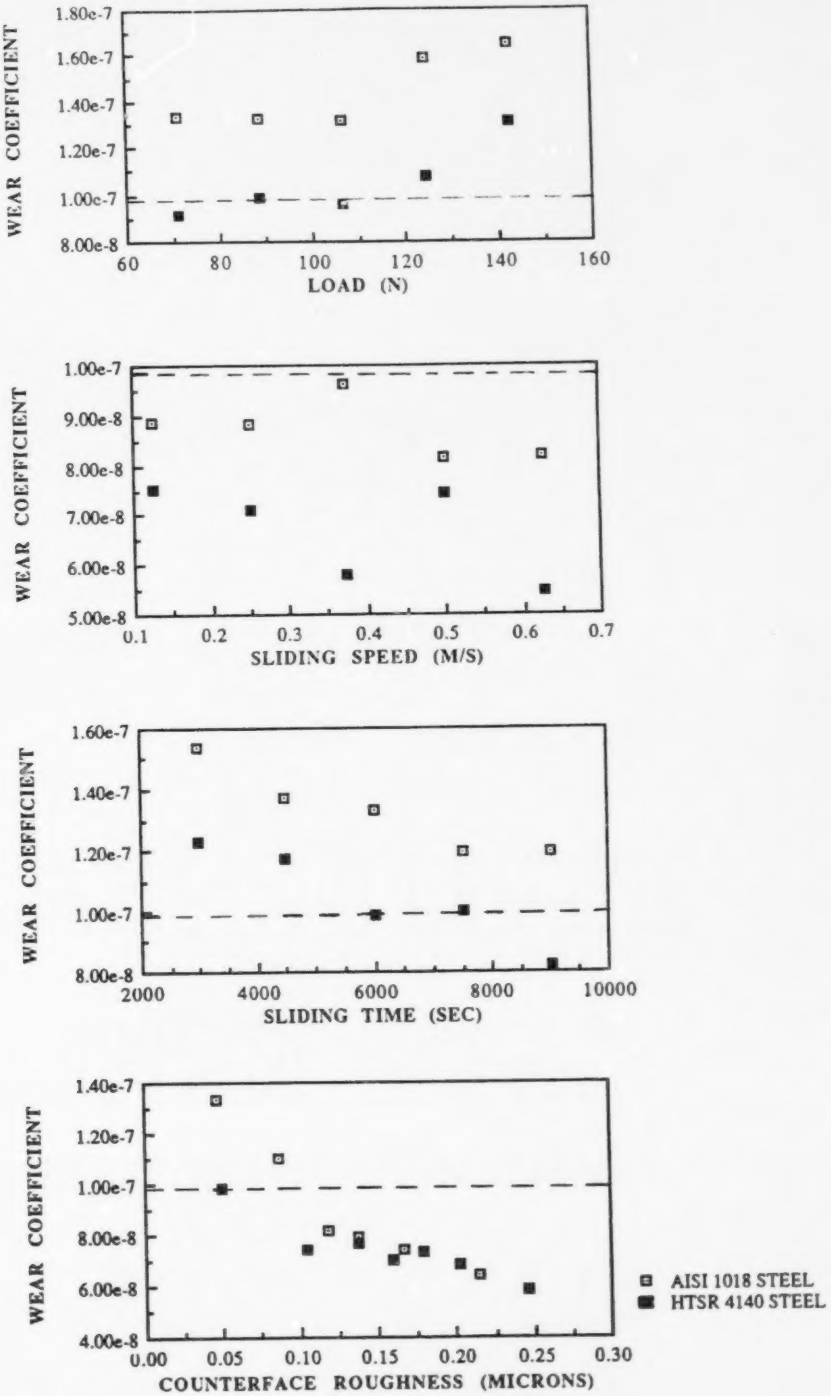

Fig. A.3.18: Sensitivity of the wear coefficient of teflon(v) with the operating variables and scatter from the average wear coefficient (dotted line) for the linear model

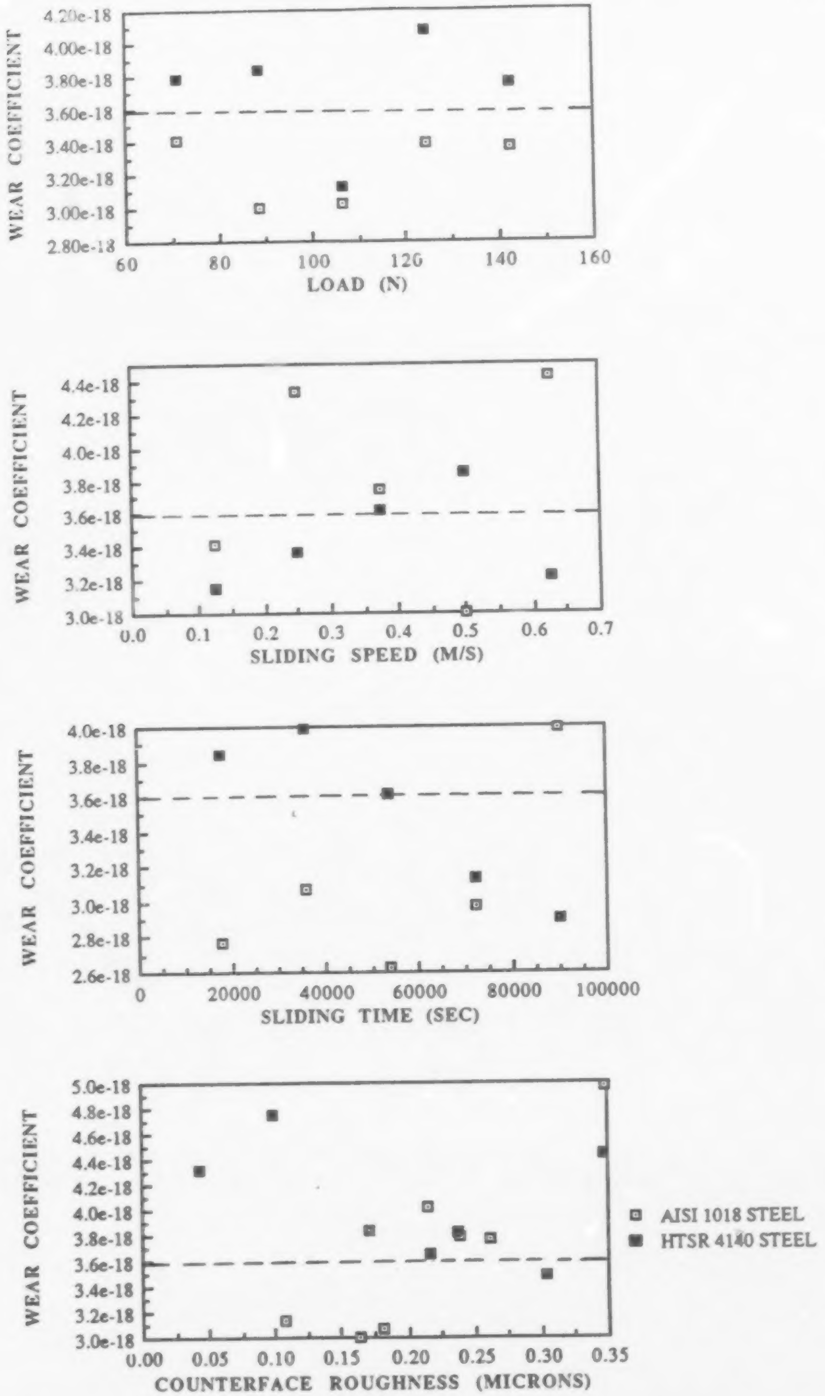

Fig. A.3.19: Sensitivity of the wear coefficient of delrin with the operating variables and scatter from the average wear coefficient (dotted line) for the non-linear model

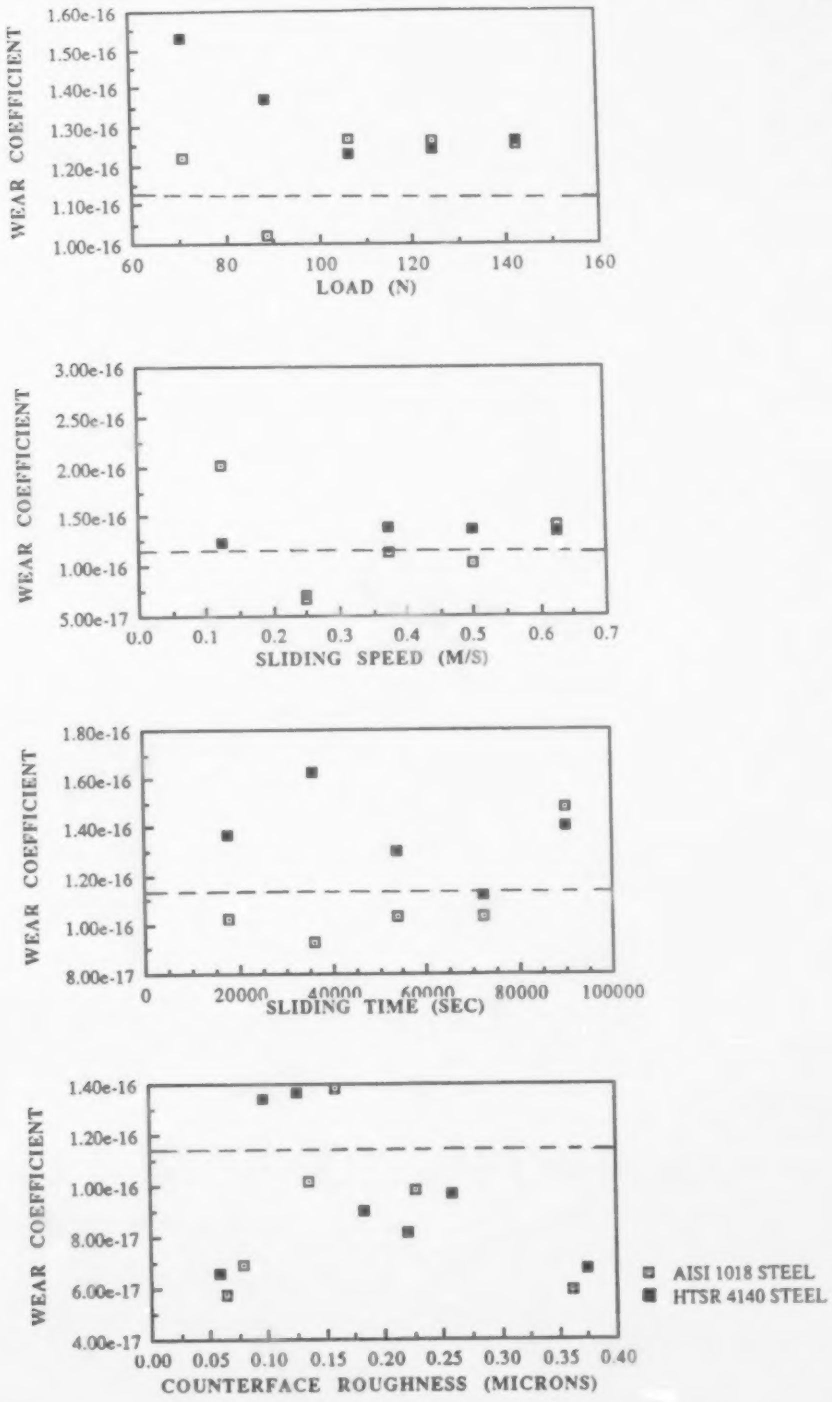

Fig. A.3.20: Sensitivity of the wear coefficient of HDPE with the operating variables and scatter from the average wear coefficient (dotted line) for the non-linear model

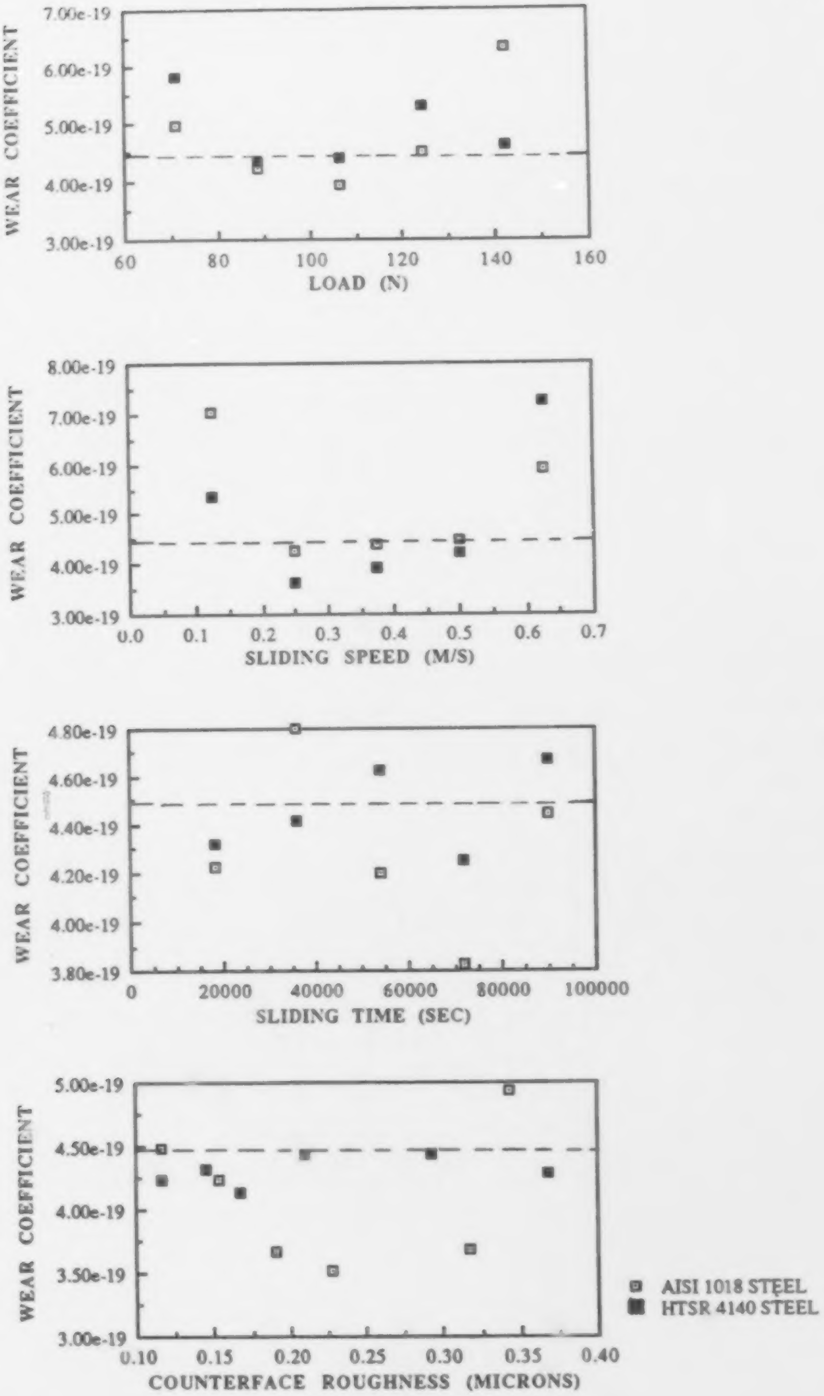

Fig. A.3.21: Sensitivity of the wear coefficient of PVC with the operating variables and scatter from the average wear coefficient (dotted line) for the non-linear model

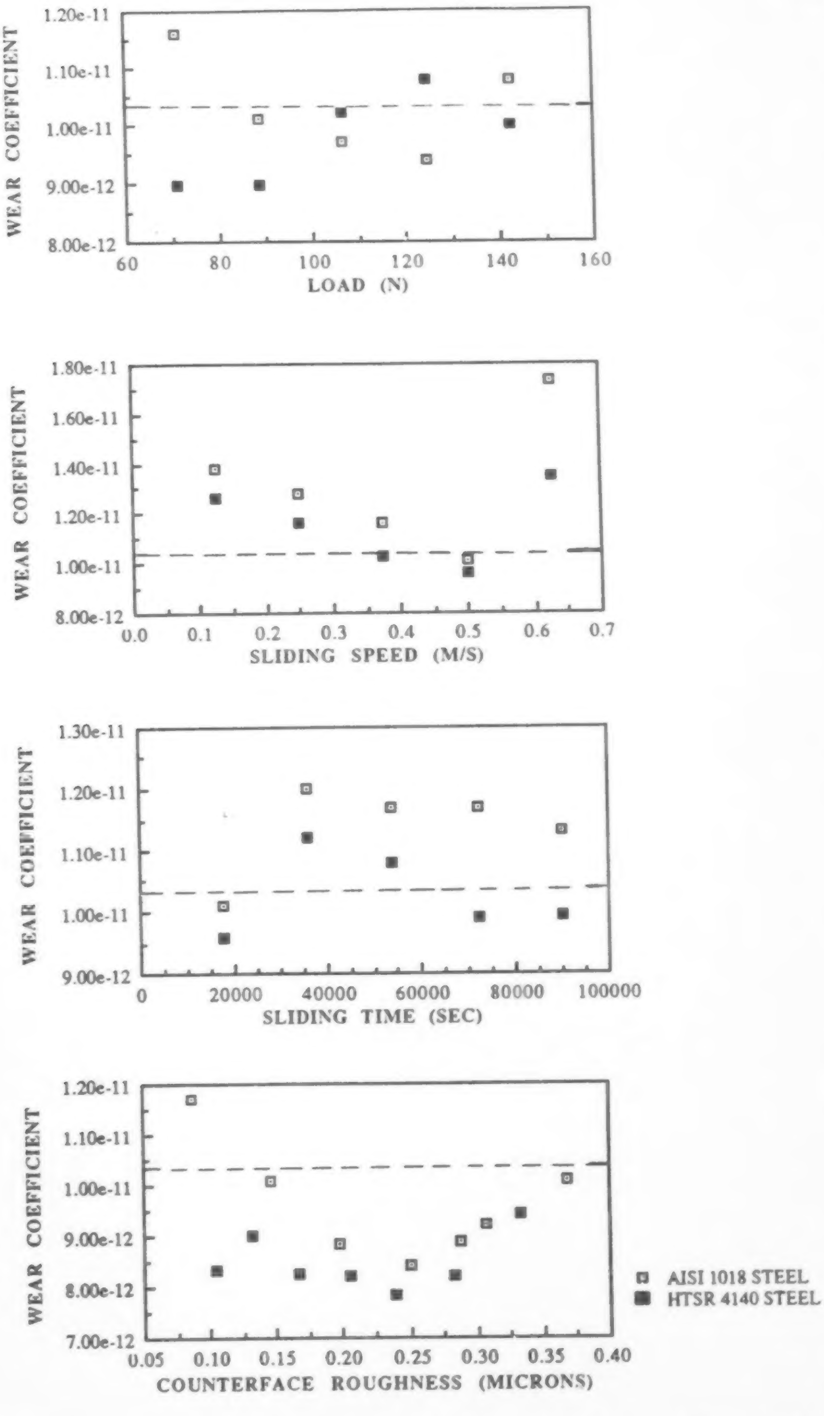

Fig. A.3.22: Sensitivity of the wear coefficient of rulon with the operating variables and scatter from the average wear coefficient (dotted line) for the non-linear model

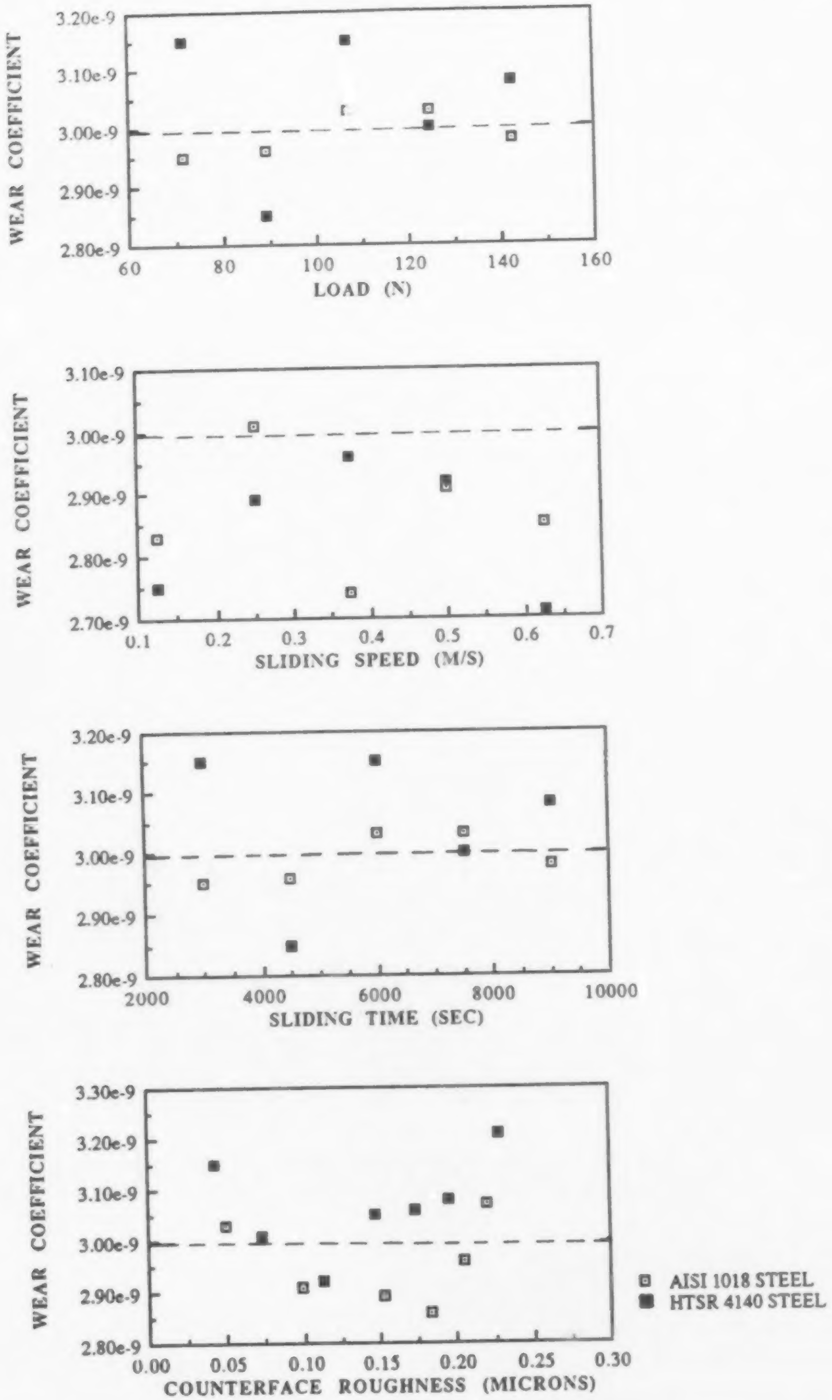

Fig. A.3.23: Sensitivity of the wear coefficient of teflon(m) with the operating variables and scatter from the average wear coefficient (dotted line) for the non-linear model

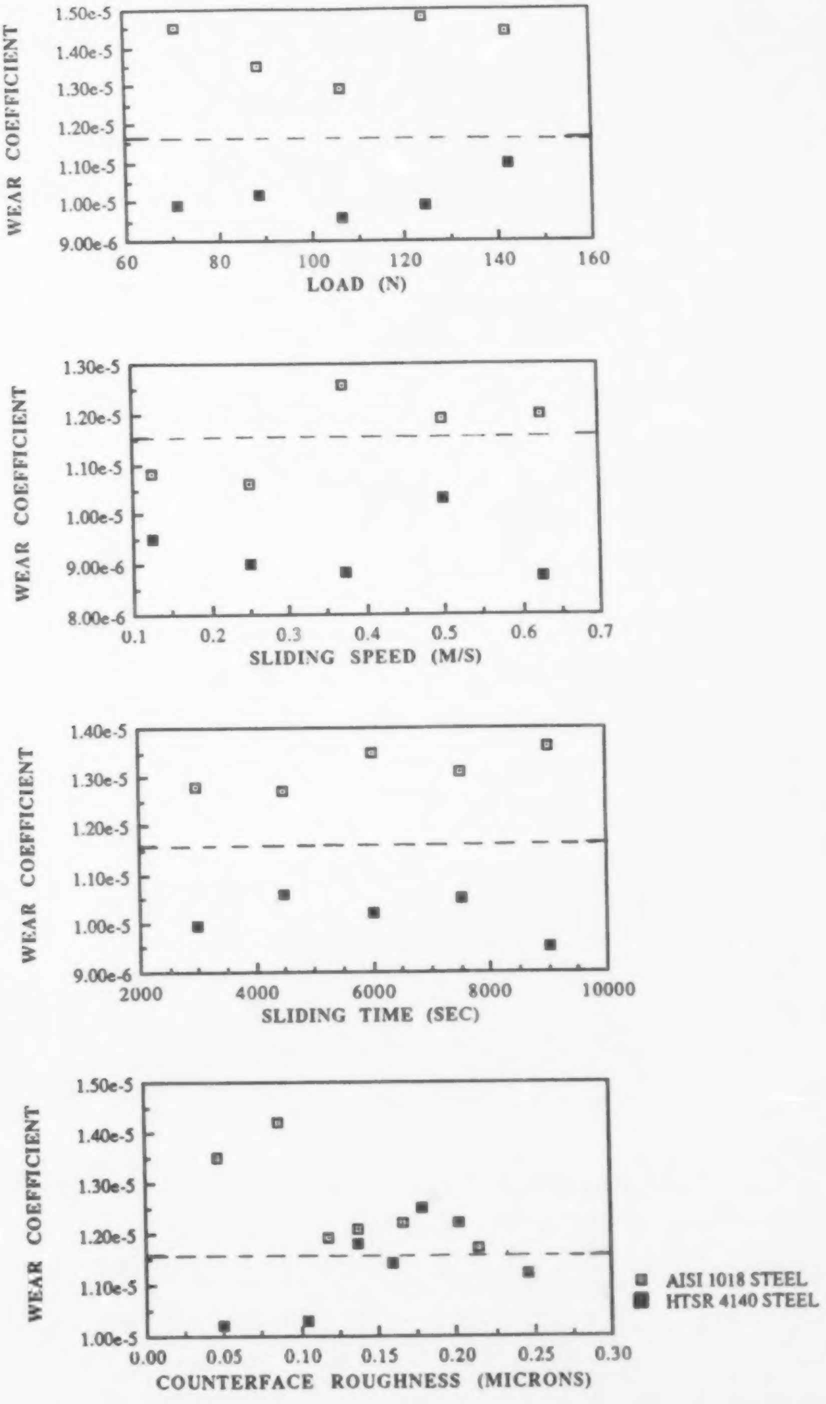

Fig. A.3.24: Sensitivity of the wear coefficient of teflon(v) with the operating variables and scatter from the average wear coefficient (dotted line) for the non-linear model